

The Star Clusters Young & Old Newsletter

edited by Giovanni Carraro, Martin Netopil, and Ernst Paunzen

<http://www.univie.ac.at/scyon/>

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Dear colleagues,

Welcome again to our new issue of the star cluster Newsletter, which, this times, comes with many news. First of all, congratulations to Richard de Grijs and the co-proposers of the new IAU star cluster commission H4, which has successfully been re-instated (<http://www.iau.org/news/announcements/detail/ann15002>).

We would like to offer two new features to expand the Newsletter and to make it an useful tool for the star cluster community.

First of all a Forum (<http://www.univie.ac.at/scyon/forum/>), namely a place where to share data, to look for missing data to complete a study, to foster new collaborations and to promote exchange of data and ideas.

Second, the Newsletter features in general a compilation of new abstracts, announcements of job advertisements and conferences. We would like to increase the scientific content of the Newsletter by offering some space to report small discoveries. These would be results that per se do not make or justify a paper, but that can be of interest for our cluster community. A figure and some text would be enough.

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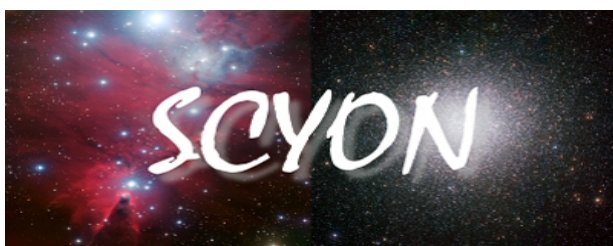
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About the Newsletter

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.

<http://www.univie.ac.at/scyon>



Star Forming Regions

The massive star population of Cygnus OB2

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We have compiled a significantly updated and comprehensive census of massive stars in the nearby Cygnus OB2 association by gathering and homogenizing data from across the literature. The census contains 169 primary OB stars, including 52 O-type stars and 3 Wolf-Rayet stars. Spectral types and photometry are used to place the stars in a Hertzsprung-Russell diagram, which is compared to both non-rotating and rotating stellar evolution models, from which stellar masses and ages are calculated. The star formation history and mass function of the association are assessed, and both are found to be heavily influenced by the evolution of the most massive stars to their end states. We find that the mass function of the most massive stars is consistent with a ‘universal’ power-law slope of $\Gamma = 1.3$. The age distribution inferred from stellar evolutionary models with rotation and the mass function suggest the majority of star formation occurred more or less continuously between 1 and 7 Myr ago, in agreement with studies of low- and intermediate-mass stars in the association. We identify a nearby young pulsar and runaway O-type star that may have originated in Cyg OB2 and suggest that the association has already seen its first supernova. Finally we use the census and mass function to calculate the total mass of the association of $16\,500^{+3800}_{-2800} M_{\odot}$, at the low end, but consistent with, previous estimates of the total mass of Cyg OB2. Despite this Cyg OB2 is still one of the most massive groups of young stars known in our Galaxy making it a prime target for studies of star formation on the largest scales.

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<http://adsabs.harvard.edu/abs/2015MNRAS.449..741W>

Galactic Open Clusters

The Gaia-ESO Survey: Discovery of a spatially extended low-mass population in the Vela OB2 association

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The nearby (distance $\sim 350\text{--}400$ pc), rich Vela OB2 association, includes γ^2 Velorum, one of the most massive binaries in the solar neighbourhood and an excellent laboratory for investigating the formation and early evolution of young clusters. Recent Gaia-ESO survey observations have led to the discovery of two kinematically distinct populations in the young (10–15 Myr) cluster immediately surrounding γ^2 Velorum. Here we analyse the results of Gaia-ESO survey observations of NGC 2547, a 35 Myr cluster located two degrees south of γ^2 Velorum. The radial velocity distribution of lithium-rich pre-main sequence stars shows a secondary population that is kinematically distinct from and younger than NGC 2547. The radial velocities, lithium absorption lines, and the positions in a colour-magnitude diagram of this secondary population are consistent with those of one of the components discovered around γ^2 Velorum. This result shows that there is a young, low-mass stellar population spread over at least several square degrees in the Vela OB2 association. This population could have originally been part of a cluster around γ^2 Velorum that expanded after gas expulsion or formed in a less dense environment that is spread over the whole Vela OB2 region.

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<http://www.aanda.org/articles/aa/abs/2015/02/aa25367-14/aa25367-14.html>

Comprehensive abundance analysis of red giants in the open clusters NGC 1342, 1662, 1912, 2354 and 2447

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We have observed high-dispersion echelle spectra of red giant members in the five open clusters NGC 1342, NGC 1662, NGC 1912, NGC 2354 and NGC 2447 and determined their radial velocities and chemical compositions. These are the first chemical abundance measurements for all but NGC 2447. We combined our clusters from this and previous papers with a sample drawn from the literature for which we remeasured the chemical abundances to establish a common abundance scale. With this homogeneous sample of open clusters, we study the relative elemental abundances of stars in open clusters in comparison with field stars as a function of age and metallicity. We find a range of mild enrichment of heavy (Ba-Eu) elements in young open cluster giants over field stars of the same metallicity. Our analysis supports that the youngest stellar generations in cluster might be under-represented by the solar neighbourhood field stars.

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The little-studied cluster Berkeley 90. I. LS III +46 11: a very massive O3.5 If* + O3.5 If* binary.

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It appears that most (if not all) massive stars are born in multiple systems. At the same time, the most massive binaries are hard to find due to their low numbers throughout the Galaxy and the implied large distances and extinctions. We want to study: [a] LS III +46 11, identified in this paper as a very massive binary; [b] another nearby massive system, LS III +46 12; and [c] the surrounding stellar cluster, Berkeley 90. Most of the data used in this paper are multi-epoch high-S/N optical spectra though we also use Lucky Imaging and archival photometry. The spectra are reduced with devoted pipelines and processed with our own software, such as a spectroscopic-orbit code, CHORIZOS, and MGB. LS III +46 11 is identified as a new very-early-O-type spectroscopic binary [O3.5 If* + O3.5 If*] and LS III +46 12 as another early O-type system [O4.5 V((f))]. We measure a 97.2-day period for LS III +46 12 and derive minimum masses of $38.80 \pm 0.83 M_{\odot}$ and $35.60 \pm 0.77 M_{\odot}$ for its two stars. We measure the extinction to both stars, estimate the distance, search for optical companions, and study the surrounding cluster. In doing so, a variable extinction is found as well as discrepant results for the distance. We discuss possible explanations and suggest that LS III +46 12 may be a hidden binary system, where the companion is currently undetected.

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<http://arxiv.org/abs/1504.06977>

WIYN Open Cluster Study. LXIII. Abundances in the Super-metal-rich Open Cluster NGC 6253 from Hydra Spectroscopy of the 7774 Å Oxygen Triplet Region

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We present a spectroscopic abundance analysis of the old, super-metal-rich open cluster NGC 6253, with emphasis on its O abundance. High-dispersion, 7774 Å O i triplet region spectra of 47 stars were obtained using Hydra II on the CTIO Blanco 4 m. Radial velocity analysis confirms 39 stars consistent with single star membership, primarily at the turnoff. Thirty-six of these are included in our abundance analysis. Our differential analysis relative to the Sun yields primarily scaled-solar values, with weighted cluster averages of $[O/H] = +0.440 \pm 0.020$, $[Fe/H] = +0.445 \pm 0.014$, $[Al/H] = +0.487 \pm 0.020$, $[Si/H] = +0.504 \pm 0.018$, and $[Ni/H] = +0.702 \pm 0.018$ (where the errors are σ_{μ}). We discuss possible origins for the three known super-metal-rich clusters based upon their abundance patterns, Galactic locations, and space motions. The abundance patterns of NGC 6253 are very similar to those of NGC 6791 and NGC 6583. With the possible exception of oxygen, the abundances of these clusters are all close to scaled-solar, and they are similar to patterns seen in metal-rich disk dwarfs and giants. However, they also seem to differ from those of metal-rich bulge stars. We demonstrate that NGC 6253 is unusually oxygen rich (in $[O/H]$) for its 3.3 Gyr age. While we find $[O/Fe]$ to be scaled-solar for NGC 6253, the more recently reported values for NGC 6791 show a large variation, from values close to scaled-solar down to values at least a factor of two below scaled-solar. We discuss the possibility that the scaled-solar $[O/Fe]$ abundances of NGC 6253 and NGC 6791 might reflect a

flattening of the Galactic [O/Fe] versus [Fe/H] relationship. This possibility may be consistent with disk star abundance data, which show an apparent “floor” at [O/Fe] ~ -0.1 for [Fe/H] > 0 , and with chemical evolution model results, which may predict such a flattening due to a decrease in supernova Fe yields at super-solar-metallicities. Orbit solutions for NGC 6791 allow that it may have formed in the inner disk and was then kicked out, but the origins of the other two much younger clusters remain mysterious. We re-evaluate the age of NGC 6583 in view of the evidence that the cluster is super-metal-rich, and confirm a probable age less than 1 Gyr (best range: 500–900 Myr). We also argue that it is unlikely the cluster is more than 3 kpc away (best range: 2–3 kpc) if the apparent turnoff, main sequence, and giants are all cluster members.

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<http://iopscience.iop.org/1538-3881/149/4/141/article>

Evidence of tidal distortions and mass loss from the old open cluster NGC 6791

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We present the first evidence of clear signatures of tidal distortions in the density distribution of the fascinating open cluster NGC 6791. We used deep and wide-field data obtained with the Canada-France-Hawaii-Telescope covering a 2×2 square degrees area around the cluster. The two-dimensional density map obtained with the optimal matched filter technique shows a clear elongation and an irregular distribution starting from $\sim 300''$ from the cluster center. At larger distances, two tails extending in opposite directions beyond the tidal radius are also visible. These features are aligned to both the absolute proper motion and to the Galactic center directions. Moreover, other overdensities appear to be stretched in a direction perpendicular to the Galactic plane. Accordingly to the behaviour observed in the density map, we find that both the surface brightness and the star count density profiles reveal a departure from a King model starting from $\sim 600''$ from the center. These observational evidence suggest that NGC 6791 is currently experiencing mass loss likely due to gravitational shocking and interactions with the tidal field. We use this evidence to argue that NGC 6791 should have lost a significant fraction of its original mass. A larger initial mass would in fact explain why the cluster survived so long. Using available recipes based on analytic studies and N-body simulations, we derived the expected mass loss due to stellar evolution and tidal interactions and estimated the initial cluster mass to be $M_{ini} = (1.5-4) \times 10^5 M_{\odot}$.

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<http://adsabs.harvard.edu/abs/2015MNRAS.449.1811D>

Insights into the properties of the Local (Orion) spiral arm. NGC 2302: First results and description of the program

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The spiral structure of the Milky Way is highly uncertain and is the subject of much discussion nowadays. We present the first result from a program that determines the properties of the Local spiral arm (LOA), together with a full description of the program. In this context we have made a comprehensive study of the young LOA open cluster NGC 2302, which includes a UBVRI photometric analysis and determination of its kinematic properties – proper motion and radial velocity – and of its orbital parameters. We determined the mean PM of NGC 2302 relative to the local field of disk stars, and, through a comparison with the UCAC4 catalog, we transformed this relative PM into an absolute one. Using medium-resolution spectroscopy of 26 stars in the field of NGC 2302, we derived its mean RV. Isochrone fits to the photometric diagrams allowed us to determine the fundamental parameters of NGC 2302, including reddening, distance, and age. The kinematic data and derived distance allowed us to determine the space motion of NGC 2302. This was done by adopting a time-independent, axisymmetric, and fully analytic gravitational potential for the MW. We obtained an absolute PM for NGC 2302 of $(\mu\alpha \cos\delta, \mu\delta) = (-2.09, -2.11)$ mas/yr, with standard errors of 0.410 and 0.400 mas/yr. The mean RV of NGC 2302 turned out to be 31.2 km/sec with a standard error of 0.7 km/sec. Isochrone fits displaced for this reddening and for a distance modulus of $(m-M)_0 = 10.69$ indicate an age of $\log(t) = 7.90-8.00$ with a slight tendency toward the younger age. Inspection of the shape of the orbit of NGC 2302 and the resulting orbital parameters indicate that it is a typical population I object.

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Radial velocities and metallicities from infrared Ca II triplet spectroscopy of open clusters II. Berkeley 23, King 1, NGC 559, NGC 6603 and NGC 7245

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Open clusters are key to studying the formation and evolution of the Galactic disc. However, there is a deficiency of radial velocity and chemical abundance determinations for open clusters in the literature. We intend to increase the number of determinations of radial velocities and metallicities from spectroscopy for open clusters. We acquired medium-resolution spectra ($R \sim 8000$) in the infrared region Ca II triplet lines ($\sim 8500 \text{ \AA}$) for several stars in five open clusters with the long-slit IDS spectrograph on the 2.5 m Isaac Newton Telescope (Roque de los Muchachos Observatory, Spain). Radial velocities were obtained by cross-correlation fitting techniques. The relationships available in the literature between the strength of infrared Ca II lines and metallicity were also used to derive the metallicity for each cluster. We obtain $\langle V_r \rangle = 48.6 \pm 3.4, -58.4 \pm 6.8, 26.0 \pm 4.3$ and $-65.3 \pm 3.2 \text{ km s}^{-1}$ for Berkeley 23, NGC 559, NGC 6603 and NGC 7245, respectively. We found $[\text{Fe}/\text{H}] = -0.25 \pm 0.14$ and -0.15 ± 0.18 for NGC 559 and NGC 7245, respectively. Berkeley 23 has a low metallicity, $[\text{Fe}/\text{H}] = -0.42 \pm 0.13$, similar to other open clusters in the outskirts of the Galactic disc. In contrast, we derived a high metallicity ($[\text{Fe}/\text{H}] = +0.43 \pm 0.15$) for NGC 6603, which places this system among the

most metal rich known open clusters. To our knowledge, this is the first determination of radial velocities and metallicities from spectroscopy for these clusters, except NGC 6603, for which radial velocities had been previously determined. We have also analysed ten stars in the line of sight to King 1. Because of the large dispersion obtained in both radial velocity and metallicity, we cannot be sure that we have sampled true cluster members.

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<http://xxx.unizar.es/abs/1504.01240>

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Testing the chemical tagging technique with open clusters

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Stars are born together from giant molecular clouds and, if we assume that the priors were chemically homogeneous and well-mixed, we expect them to share the same chemical composition. Most of the stellar aggregates are disrupted while orbiting the Galaxy and most of the dynamic information is lost, thus the only possibility of reconstructing the stellar formation history is to analyze the chemical abundances that we observe today. The chemical tagging technique aims to recover disrupted stellar clusters based merely on their chemical composition. We evaluate the viability of this technique to recover co-natal stars that are no longer gravitationally bound. Open clusters are co-natal aggregates that have managed to survive together. We compiled stellar spectra from 31 old and intermediate-age open clusters, homogeneously derived atmospheric parameters, and 17 abundance species, and applied machine learning algorithms to group the stars based on their chemical composition. This approach allows us to evaluate the viability and efficiency of the chemical tagging technique. We found that stars at different evolutionary stages have distinct chemical patterns that may be due to NLTE effects, atomic diffusion, mixing, and biases. When separating stars into dwarfs and giants, we observed that a few open clusters show distinct chemical signatures while the majority show a high degree of overlap. This limits the recovery of co-natal aggregates by applying the chemical tagging technique. Nevertheless, there is room for improvement if more elements are included and models are improved.

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Galactic Globular Clusters

G2C2 - III. Structural parameters for Galactic globular clusters in SDSS passbands

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We use our Galactic Globular Cluster Catalog (G2C2) photometry for 111 Galactic globular clusters (GC) in g and z , as well as r and i photometry for a subset of 60 GCs and u photometry for 22 GCs, to determine the structural parameters assuming King (1962) models. In general, the resulting core radii are in good comparison with the current literature values. However, our half-light radii are slightly lower than the literature. The concentrations (and therefore also the tidal radii) are poorly constrained mostly because of the limited radial extent of our imaging. Therefore, we extensively discuss the effects of a limited field-of-view on the derived parameters using mosaicked SDSS data, which do not suffer from this restriction. We also illustrate how red giant branch (RGB) stars in cluster cores can stochastically induce artificial peaks in the surface brightness profiles. The issues related to these bright stars are scrutinised based on both our photometry and simulated clusters. We also examine colour gradients and find that the strongest central colour gradients are caused by central RGB stars and thus not representative for the cluster light or colour distribution. We recover the known relation between the half-light radius and the Galactocentric distance in the g -band, but find a lower slope for redder filters. We did not find a correlation between the scatter on this relation and other cluster properties. We find tentative evidence for a correlation between the half-light radii and the $[\text{Fe}/\text{H}]$, with metal-poor GCs being larger than metal-rich GCs. However, we conclude that this trend is caused by the position of the clusters in the Galaxy, with metal-rich clusters being more centrally located.

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<http://adsabs.harvard.edu/abs/2015MNRAS.450.2692V>

G2C2 - IV: A novel approach to study the radial distributions of multiple populations in Galactic globular clusters

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We use the HB morphology of 48 Galactic GCs to study the radial distributions of the different stellar populations known to exist in globular clusters. Assuming that the (extremely) blue HB stars correspond to stars enriched in Helium and light elements, we compare the radial distributions of stars selected according to colour on the HB to trace the distribution of the secondary stellar populations in globular clusters. Unlike other cases, our data show that the populations are well mixed in 80% of the cases studied. This provides some constraints on the mechanisms proposed to pollute the interstellar medium in young globular clusters.

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<http://adsabs.harvard.edu/abs/2015arXiv150406509V>

The Gaia-ESO Survey: Detailed Abundances in the Metal-poor Globular Cluster NGC 4372

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We present the abundance analysis for a sample of 7 red giant branch stars in the metal-poor globular cluster NGC 4372 based on UVES spectra acquired as part of the Gaia-ESO Survey. This is the first extensive study of this cluster from high resolution spectroscopy. We derive abundances of O, Na, Mg, Al, Si, Ca, Sc, Ti, Fe, Cr, Ni, Y, Ba, and La. We find a metallicity of $[\text{Fe}/\text{H}] = -2.19 \pm 0.03$ and find no evidence for a metallicity spread. This metallicity makes NGC 4372 one of the most metal-poor galactic globular clusters. We also find an α -enhancement typical of halo globular clusters at this metallicity. Significant spreads are observed in the abundances of light elements. In particular we find a Na-O anti-correlation. Abundances of O are relatively high compared with other globular clusters. This could indicate that NGC 4372 was formed in an environment with high O for its metallicity. A Mg-Al spread is also present which spans a range of more than 0.5 dex in Al abundances. Na is correlated with Al and Mg abundances at a lower significance level. This pattern suggests that the Mg-Al burning cycle is active. This behavior can also be seen in giant stars of other massive, metal-poor clusters. A relation between light and heavy s-process elements has been identified.

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Updated census of RR Lyrae stars in the globular cluster ω Centauri (NGC 5139)

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ω Centauri (NGC 5139) contains many variable stars of different types and, in particular, more than one hundred RR Lyrae stars. This enabled gathering a homogeneous sample (in terms of instrument, image quality, and time coverage) of high-quality near-infrared (NIR) RR Lyrae light curves by performing an extensive time-series campaign aimed at this object. We have conducted a variability survey of ω Cen in the NIR, using ESO's 4.1 m Visible and Infrared Survey Telescope for Astronomy (VISTA). This is the first paper of a series describing our results. ω Cen was observed using VIRCAM mounted on VISTA. A total of 42 epochs in J and 100 epochs in KS were obtained, distributed over a total timespan of 352 days. Point-spread function photometry was performed using DAOPHOT in the inner and DoPhot in the outer regions of the cluster. Periods of the known variable stars were improved when necessary using an ANOVA analysis. We collected an unprecedented homogeneous and complete NIR catalog of RR Lyrae stars in the field of ω Cen, allowing us to study for the first time all the RR Lyrae stars associated with the cluster, except for four stars that are located far away from the cluster center. We derived membership status, subclassifications between RRab and RRc subtypes, periods, amplitudes, and mean magnitudes for all the stars in our sample. Additionally, four new RR Lyrae stars were discovered, two of which are very likely cluster members. We also discuss here the distribution of ω Cen stars in the Bailey (period-amplitude) diagram. We provide reference lines in this plane for both Oosterhoff Type I (OoI) and Oosterhoff Type II (OoII) components in J and KS. We clarify the status of many (candidate) RR Lyrae stars that have been reported as unclear in previous studies. This includes stars with anomalous positions in the color-magnitude diagram,

uncertain periods or/and variability types, and possible field interlopers. We conclude that ω Cen hosts a total of 88 RRab and 101 RRC stars, which makes for a grand total of 189 probable members. We confirm that most RRab stars in the cluster appear to belong to an OoII component, as previously found using visual data.

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<http://www.aanda.org/articles/aa/abs/2015/05/aa24838-14/aa24838-14.html>

When do stars in 47 Tucanae lose their mass?

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By examining the diffusion of young white dwarfs through the core of the globular cluster 47 Tucanae, we estimate the time when the progenitor star lost the bulk of its mass to become a white dwarf. We find this to be not earlier than 40 Myr before the star reaches the tip of the asymptotic giant branch. According to stellar evolution models of the white-dwarf progenitors in 47 Tucanae, we find this epoch to coincide approximately with the star ascending the asymptotic-giant branch and well after the helium flash. With the current data and analysis we cannot exclude some mass loss on the red-giant branch, but we argue that the bulk of the mass loss must occur very late in the star's history on the asymptotic-giant branch. We also confront the observed magnitudes of stars on the horizontal branch in 47 Tucanae and find that they are consistent with the latest theoretical models of the horizontal branch stars of 0.8–0.9 M_{\odot} , further supporting the conclusion that the stars in 47 Tucanae and likewise in other clusters lose the bulk of their mass on the asymptotic-giant branch.

Submitted to : Astrophysical Journal

<http://arxiv.org/abs/1502.07306>

Evolution of long-lived globular cluster stars I. Grid of stellar models with helium enhancement at $[\text{Fe}/\text{H}] = -1.75$

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Our understanding of the formation and early evolution of globular clusters (GCs) has been totally overthrown with the discovery of the peculiar chemical properties of their long-lived host stars. As a consequence, the interpretation of the observed color-magnitude diagrams and of the properties of the GC stellar populations requires the use of stellar models computed with relevant chemical compositions. We present a grid of 224 stellar evolution models for low-mass stars with initial masses between 0.3 and 1.0 M_{\odot} and initial helium mass fraction between 0.248 and 0.8 computed for $[\text{Fe}/\text{H}] = -1.75$ with the stellar evolution code STAREVOL. This grid is made available to the community. We explore the implications of the assumed initial chemical distribution for the main properties of the stellar models: evolution paths in the Hertzsprung-Russel diagram (HRD), duration and characteristics of the main evolutionary phases, and the chemical nature of the white dwarf remnants. We also provide the ranges in initial stellar mass and helium content of the stars that populate the different regions of the HRD at the ages of 10 and 13.4 Gyr, which are typical for Galactic GCs.

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<http://adsabs.harvard.edu/abs/2015arXiv150401878C>

The most distant clusters

How elevated is the dynamical-to-stellar mass ratio of the ultracompact dwarf S999?

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Here we present new Keck Echelle Spectrograph and Imager high-resolution spectroscopy and deep archival Hubble Space Telescope/Advanced Camera for Surveys imaging for S999, an ultracompact dwarf in the vicinity of M87, which was claimed to have an extremely high dynamical-to-stellar mass ratio. Our data increase the total integration times by a factor of 5 and 60 for spectroscopy and imaging, respectively. This allows us to constrain the stellar population parameters for the first time (simple stellar population equivalent age = $7.6_{-1.6}^{+2.0}$ Gyr; $[Z/H] = -0.95_{-0.10}^{+0.12}$; $[\alpha / \text{Fe}] = 0.34_{-0.12}^{+0.10}$). Assuming a Kroupa stellar initial mass function, the stellar population parameters and luminosity ($M_{F814W} = -12.13 \pm 0.06$ mag) yield a stellar mass of $M_* = 3.9_{-0.6}^{+0.9} \times 10^6 M_\odot$, which we also find to be consistent with near-infrared data. Via mass modelling, with our new measurements of velocity dispersion ($\sigma = 27 \pm 2 \text{ km s}^{-1}$) and size ($R_e = 20.9 \pm 1.0 \text{ pc}$), we obtain an elevated dynamical-to-stellar mass ratio $M_{dyn}/M_* = 8.2$ (with a range $5.6 \leq M_{dyn}/M_* \leq 11.2$). Furthermore, we analyse the surface brightness profile of S999, finding only a small excess of light in the outer parts with respect to the fitted Sérsic profile, and a positive colour gradient. Taken together these observations suggest that S999 is the remnant of a much larger galaxy that has been tidally stripped. If so, the observed elevated mass ratio may be caused by mechanisms related to the stripping process: the existence of a massive central black hole or internal kinematics that are out of equilibrium due to the stripping event. Given the observed dynamical-to-stellar mass ratio we suggest that S999 is an ideal candidate to search for the presence of an overly massive central black hole.

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Dynamical evolution - Simulations

Close encounters involving free-floating planets in star clusters

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Instabilities in planetary systems can result in the ejection of planets from their host system, resulting in free-floating planets (FFPs). If this occurs in a star cluster, the FFP may remain bound to the star cluster for some time and interact with the other cluster members until it is ejected. Here, we use N-body simulations to characterize close star-planet and planet-planet encounters and the dynamical fate of the FFP population in star clusters containing 500 – 2000 single or binary star members. We find that FFPs ejected from their planetary system at low velocities typically leave the star cluster 40% earlier than their host stars, and experience tens of close (< 1000 AU) encounters with other stars and planets before they escape. The fraction of FFPs that experiences a close encounter depends on both the stellar density and the initial velocity distribution of the FFPs. Approximately half of the close encounters occur within the first 30 Myr, and only 10% occur after 100 Myr. The periastron velocity distribution for all encounters is well-described by a modified Maxwell-Boltzmann distribution, and the periastron distance distribution is linear over almost the entire range of distances considered, and flattens off for very close encounters due to strong gravitational focusing. Close encounters with FFPs can perturb existing planetary systems and their debris structures, and they can result in re-capture of FFPs. In addition, these FFP populations may be observed in young star clusters in imaging surveys; a comparison between observations and dynamical predictions may provide clues to the early phases of stellar and planetary dynamics in star clusters.

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NBODY6++GPU: Ready for the gravitational million-body problem

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Accurate direct N-body simulations help to obtain detailed information about the dynamical evolution of star clusters. They also enable comparisons with analytical models and Fokker-Planck or Monte-Carlo methods. NBODY6 is a well-known direct N-body code for star clusters, and NBODY6++ is the extended version designed for large particle number simulations by supercomputers. We present NBODY6++GPU, an optimized version of NBODY6++ with hybrid parallelization methods (MPI, GPU, OpenMP, and AVX/SSE) to accelerate large direct N-body simulations, and in particular to solve the million-body problem. We discuss the new features of the NBODY6++GPU code, benchmarks, as well as the first results from a simulation of a realistic globular cluster initially containing a million particles. For million-body simulations, NBODY6++GPU is 400 – 2000 times faster than NBODY6 with 320 CPU cores and 32 NVIDIA K20X GPUs. With this computing cluster specification, the simulations of million-body globular clusters including 5% primordial binaries require about an hour per half-mass crossing time.

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Biases in the determination of dynamical parameters of star clusters: today and in the Gaia era

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The structural and dynamical properties of star clusters are generally derived by means of the comparison between steady-state analytic models and the available observables. With the aim of studying the biases of this approach, we fitted different analytic models to simulated observations obtained from a suite of direct N-body simulations of star clusters in different stages of their evolution and under different levels of tidal stress to derive mass, mass function and degree of anisotropy. We find that masses can be under/over-estimated up to 50% depending on the degree of relaxation reached by the cluster, the available range of observed masses and distances of radial velocity measures from the cluster center and the strength of the tidal field. The mass function slope appears to be better constrainable and less sensitive to model inadequacies unless strongly dynamically evolved clusters and a non-optimal location of the measured luminosity function are considered. The degree and the characteristics of the anisotropy developed in the N-body simulations are not adequately reproduced by popular analytic models and can be detected only if accurate proper motions are available. We show how to reduce the uncertainties in the mass, mass-function and anisotropy estimation and provide predictions for the improvements expected when Gaia proper motions will be available in the near future.

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Dependency of dynamical ejections of O stars on the masses of very young star cluster

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Massive stars can be efficiently ejected from their birth clusters through encounters with other massive stars. We study how the dynamical ejection fraction of O star systems varies with the masses of very young star clusters, M_{ecl} , by means of direct N -body calculations. We include diverse initial conditions by varying the half-mass radius, initial mass-segregation, initial binary fraction and orbital parameters of the massive binaries. The results show robustly that the ejection fraction of O star systems exhibits a maximum at a cluster mass of $10^{3.5} M_{\odot}$ for all models, even though the number of the ejected systems increases with cluster mass. We show that lower mass clusters ($M_{\text{ecl}} \approx 400 M_{\odot}$) are the dominant sources for populating the Galactic field with O stars by dynamical ejections, considering the mass function of embedded clusters. About 15 per cent (up to ≈ 38 per cent, depending on the cluster models) of O stars of which a significant fraction are binaries, and which would have formed in a ≈ 10 Myr epoch of star formation in a distribution of embedded clusters, will be dynamically ejected to the field. Individual clusters may eject 100 per cent of their original O star content. A large fraction of such O stars have velocities up to only 10 km s^{-1} . Synthesising a young star cluster mass function it follows, given the stellar-dynamical results presented here, that the observed fractions of field and runaway O stars, and the binary fractions among them can be well understood theoretically if all O stars form in embedded clusters.

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Multiple populations in globular clusters: the distinct kinematic imprints of different formation scenarios

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Several scenarios have been proposed to explain the presence of multiple stellar populations in globular clusters. Many of them invoke multiple generations of stars to explain the observed chemical abundance anomalies, but it has also been suggested that self-enrichment could occur via accretion of ejecta from massive stars onto the circumstellar disc of low-mass pre-main sequence stars. These scenarios imply different initial conditions for the kinematics of the various stellar populations. Given some net angular momentum initially, models for which a second generation forms from gas that collects in a cooling flow into the core of the cluster predict an initially larger rotational amplitude for the polluted stars compared to the pristine stars. This is opposite to what is expected from the accretion model, where the polluted stars are the ones crossing the core and are on preferentially radial (low-angular momentum) orbits, such that their rotational amplitude is lower. Here we present the results of a suite of N-body simulations with initial conditions chosen to capture the distinct kinematic properties of these pollution scenarios. We show that initial differences in the kinematics of polluted and pristine stars can survive to the present epoch in the outer parts of a large fraction of Galactic globular clusters. The differential rotation of pristine and polluted stars is identified as a unique kinematic signature that could allow us to distinguish between various scenarios, while other kinematic imprints are generally very similar from one scenario to the other.

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Galactic orbital motions of star clusters: static versus semicosmological time-dependent Galactic potentials

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In order to understand the orbital history of Galactic halo objects, such as globular clusters, authors usually assume a static potential for our Galaxy with parameters that appear at the present-day. According to the standard paradigm of galaxy formation, galaxies grow through a continuous accretion of fresh gas and a hierarchical merging with smaller galaxies from high redshift to the present day. This implies that the mass and size of disc, bulge, and halo change with time. We investigate the effect of assuming a live Galactic potential on the orbital history of halo objects and its consequences on their internal evolution. We numerically integrate backwards the equations of motion of different test objects located in different Galactocentric distances in both static and time-dependent Galactic potentials in order to see if it is possible to discriminate between them. We show that in a live potential, the birth of the objects, 13 Gyr ago, would have occurred at significantly larger Galactocentric distances, compared to the objects orbiting in a static potential. Based on the direct N -body calculations of star clusters carried out with collisional N -body code, NBODY6, we also discuss the consequences of the time-dependence of a Galactic potential on the early- and long-term evolution of star clusters in a simple way, by comparing the evolution of two star clusters embedded in galactic models, which represent the galaxy at present and 12 Gyr ago, respectively. We show that assuming a static potential over a Hubble time for our Galaxy as it is often done, leads to an enhancement of mass-loss, an overestimation of the dissolution rates of globular clusters, an underestimation of the final size of star clusters, and a shallower stellar mass function.

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Miscellaneous**Binary Black Hole Mergers from Globular Clusters: Implications for Advanced LIGO****C. L. Rodriguez**¹, **M. Morscher**¹, **B. Pattabiraman**^{1,2}, and **3 co-authors**

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The predicted rate of binary black hole mergers from galactic fields can vary over several orders of magnitude and is extremely sensitive to the assumptions of stellar evolution. But in dense stellar environments such as globular clusters, binary black holes form by well-understood gravitational interactions. In this letter, we study the formation of black hole binaries in an extensive collection of realistic globular cluster models. By comparing these models to observed Milky Way and extragalactic globular clusters, we find that the mergers of dynamically-formed binaries could be detected at a rate of 100 per year, potentially dominating the binary black hole merger rate. We also find that a majority of cluster-formed binaries are more massive than their field-formed counterparts, suggesting that Advanced LIGO could identify certain binaries as originating from dense stellar environments.

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Ph.D. (dissertation) summaries

The Dynamical Evolution of Stellar-Mass Black Holes in Dense Star Clusters

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Globular clusters are gravitationally bound systems containing up to $\sim 10^6$ stars, and are found ubiquitously in massive galaxies, including the Milky Way. With densities as high as $\sim 10^6$ stars per cubic parsec, they are one of the few places in the Universe where stars interact with one another. They therefore provide us with a unique laboratory for studying how gravitational interactions can facilitate the formation of exotic systems, such as X-ray binaries containing black holes, and merging double black hole binaries, which are produced much less efficiently in isolation. While telescopes can provide us with a snapshot of what these dense clusters look like at present, we must rely on detailed numerical simulations to learn about their *evolution*. These simulations are quite challenging, however, since dense star clusters are described by a complicated set of physical processes occurring on many different length and time scales, including stellar and binary evolution, weak gravitational scattering encounters, strong resonant binary interactions, and tidal stripping by the host galaxy. Until very recently, it was not possible to model the evolution of systems with millions of stars, the actual number contained in the largest clusters, including all the relevant physics required describe these systems accurately. The Northwestern Group’s Hénon Monte Carlo code, CMC, which has been in development for over a decade, is a powerful tool that can be used to construct detailed evolutionary models of large star clusters. With its recent parallelization, CMC is now capable of addressing a particularly interesting unsolved problem in astrophysics: the dynamical evolution of stellar black holes in dense star clusters. Our current understanding of the stellar initial mass function and massive star evolution suggests that young globular clusters may have formed hundreds to thousands of stellar-mass black holes, the remnants of stars with initial masses from $\sim 20 - 100 M_{\odot}$. Birth kicks from supernova explosions may eject some black holes from their birth clusters, but most should be retained initially. Using our Monte Carlo code, we have investigated the long-term dynamical evolution of globular clusters containing large numbers of stellar black holes. Our study is the first to explore in detail the dynamics of BHs in clusters through a large number of realistic simulations covering a wide range of initial conditions (cluster masses from $\sim 10^5 - 10^6 M_{\odot}$, as well as variation in other key parameters, such as the virial radius, central concentration, and metallicity), that *also* includes all the required physics. In almost all of our models we find that significant numbers of black holes (up to $\sim 10^3$) are retained all the way to the present. This is in contrast to previous theoretical expectations that most black holes should be ejected dynamically within a few Gyr. The main reason for this difference is that core collapse driven by black holes (through the Spitzer “mass segregation instability”) is easily reverted through three-body processes, and involves only a small number of the most massive black holes, while lower-mass black holes remain well-mixed with ordinary stars far from the central cusp. Thus the rapid segregation of stellar black holes does not lead to a long-term physical separation of most black holes into a dynamically decoupled inner core, as often assumed previously; this is one of the most important results of this dissertation. Combined with the recent detections of several black hole X-ray binary candidates in Galactic globular clusters, our results suggest that stellar black holes could still be present in large numbers in many globular clusters today, and that they may play a significant role in shaping the long-term dynamical evolution and the present-day dynamical structure of many clusters.

This is the abstract from the Ph.D. thesis of Meagan Morscher, done under the supervision of Prof. Frederic A. Rasio at Northwestern University, Evanston, IL, USA. For a full copy of this dissertation, contact Meagan Morscher at m.morscher@gmail.com

Conferences

Stellar Clusters: benchmarks of stellar physics and galactic evolution

(25th Evry Schatzman School on Stellar Astrophysics)

4-9 October, 2015

Banyuls sur Mer, France

<http://ees2015.sciencesconf.org/?lang=en>

Registration deadline: June 30, 2015

Feedback in the Magellanic Clouds

5-7 October, 2015

Baltimore, USA

<http://www.stsci.edu/institute/conference/fimc/>

Registration deadline: Aug. 31, 2015 (abstract submission already closed)