The Star Clusters Young & Old Newsletter

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

We hope that this new SCYON issue finds you well! We want to draw your attention that apart from the submission of "regular" abstracts there is also the possibility to provide a very short (twitter style) abstract with less than 500 characters, which can be supported by a figure to even more highlight the importance of your paper. Submissions other than paper abstracts (Job opportunities, information about new databases, surveys, tool etc.) are also always welcome! The same holds for feedback to further improve the Newsletter.

With this issue we want congratulate Vikrant Vinayak Jadav for the completion of his PhD thesis. The thesis abstract and the link to the complete thesis can be found in this issue. We wish him all the best for his future scientific career and all readers a happy, healthy and successful new Year!

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

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Picture of the issue:

Several satellite missions significantly improved our knowledge of star clusters. For example, *Gaia* provided numerous outstanding results for in particular closer objects. Furthermore, already one year after the launch of the James Webb Space Telescope, detailed views and studies are possible also for obscured and most distant clusters – and we are glad that this SCYON issue also includes some first results based on JWST data.

As picture of the issue we selected an impressive JWST NIRCam view of the Tarantula Nebula star-forming region:

Credits: NASA, ESA, CSA, STScI, Webb ERO Production Team

About the Newsletter

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

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

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

Star cluster feedback and early evolution

The galaxy-wide stellar initial mass function in the presence of cluster-to-cluster IMF variations

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We calculate the stellar integrated galactic initial mass function (IGIMF) in the presence of cluster-to-cluster variations of the IMF. Variations of the IMF for a population of coeval clusters that populate the initial cluster mass function (ICLMF) are taken into account in the form of Gaussian distribution functions of the IMF parameters. For the tapered power-law function used in this work, these are the slope at the high-mass end, Γ, the slope at the low-mass end, γ, and the characteristic mass M_{ch}. The level of variations is modeled by varying the width of the Gaussian distributions. The reference values are the standard deviations of the parameters observed for the population of young clusters in the present-day Milky Way, which are $\sigma_\Gamma = 0.6$, $\sigma_\gamma = 0.25$, and $\sigma_{M_{ch}} = 0.27$ M$_\odot$. We find that increasing the levels of dispersion for γ and Γ tends to moderately flatten the IGIMF at the low and high-mass end, respectively. The characteristic mass of the IGIMF is, however, strongly impacted by variations in M_{ch}. Increasing the value of $\sigma_{M_{ch}}$ shifts the peak of the IGIMF to lower masses, rendering the IGIMF more bottom heavy. This can provide a simple explanation for the bottom-heavy stellar mass function that is inferred for early-type galaxies since these are likely the result of a merger of disk galaxies where the physical conditions of the star-forming gas may vary significantly both in time and space in the merging system. The effect of IMF variations on the IGIMF is compared to the effects of other processes and sources of systematic variations such as those due to variations in the shape of ICLMF, the gas-phase metallicity, and the galactic star formation rate (SFR) which can potentially affect the maximum mass of stellar clusters in a galaxy and set the mean value of the characteristic mass in clusters. For the various dependencies we have explored, we found that the effect of IMF variations is a dominant factor that always affects the characteristic mass of the IGIMF. For the regimes at low metallicity where the IGIMF resembles a single power law, an increased level of IMF variations renders the IGIMF steeper and more bottom heavy, especially at low SFRs. On the other hand, variations in the IMF in the high mass regime can be easily dominated by variations in the slope of the ICLMF. We compare our results of the metallicity and SFR-dependent IGIMF to a sample of Milky Way ultra-faint dwarf (UFD) satellite galaxies that have available metallicity measurements. The present-day stellar mass function of these galaxies is a good analog to the IGIMF at the time their overall population of stars formed. We show that the slope of the stellar mass function of the UFD galaxies measured for stars in the mass range [0.4,0.8] M$_\odot$ can only be reproduced when IMF variations of the same order as those measured in the present-day Milky Way are included. Our results suggest that the inclusion of IMF variations in models of galaxy formation and evolution is of vital importance in order to improve our understanding of star formation and star formation feedback effects on galactic scales.

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Star clusters in the Milky Way and Local group

Optical linear polarization study toward Czernik 3 open cluster at different spatial scales

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We present the optical linear polarization observation of stars towards the core of the Czernik 3 cluster in the Sloan i-band. The data were obtained using the EMPOL instrument on the 1.2 m telescope at Mount Abu Observatory. We study the dust distribution towards this cluster by combining the results from our polarization observations with the data from Gaia EDR3, WISE, and the HI, ^{12}CO surveys. In addition, we use the polarimetric data of previously studied clusters within 15° of Czernik 3 to understand the large-scale dust distribution. The observational results of Czernik 3 show a large range in the degree of polarization, indicating that the dust is not uniformly distributed over the plane of the sky, even on a small scale. The distance to the Czernik 3 is constrained to 3.6 ± 0.8 kpc using the member stars in the core region identified from Gaia EDR3 astrometry. This makes it one of the most distant clusters observed for optical polarization so far. The variation of observed degree of polarization and extinction towards this cluster direction suggests the presence of at least two dust layers along this line of sight at distances of ~ 1 kpc and ~ 3.4 kpc. There is an indication of the presence of dust in the centre of the cluster, as seen from an increase in the degree of polarization and WISE W4 flux. The large-scale distribution of dust reveals the presence of a region of low dust content between the local arm and the Perseus arm.

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The Panchromatic Hubble Andromeda Treasury: Triangulum Extended Region (PHATTER). IV. Star Cluster Catalog

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We construct a catalog of star clusters from Hubble Space Telescope images of the inner disk of the Triangulum Galaxy (M33) using image classifications collected by the Local Group Cluster Search, a citizen science project hosted on the Zooniverse platform. We identify 1214 star clusters within the Hubble Space Telescope imaging footprint of the Panchromatic Hubble Andromeda Treasury: Triangulum Extended Region (PHATTER) survey. Comparing this catalog to existing compilations in the literature, 68% of the clusters are newly identified. The final catalog includes multi-band aperture photometry and fits for cluster properties via integrated light SED fitting. The cluster catalog's 50% completeness limit is ∼1500 solar masses at an age of 100 Myr, as derived from comprehensive synthetic cluster tests.

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The VISCACHA survey - V. Rejuvenating three faint SMC clusters

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We present the analysis of three faint clusters of the Small Magellanic Cloud RZ82, HW42 and RZ158. We employed the SOAR telescope instrument SAM with adaptive optics, allowing us to reach to V∼23-24 mag, unprecedentedly, a depth sufficient to measure ages of up to about 10-12 Gyr. All three clusters are resolved to their centres, and the resulting colour-magnitude diagrams (CMDs) allow us to derive ages of 3.9, 2.6, and 4.8 Gyr respectively. These results are significantly younger than previous determinations (7.1, 5.0, and 8.3 Gyr, respectively), based on integrated photometry or shallower CMDs. We rule out older ages for these clusters based on deep photometry and statistical isochrone fitting. We also estimate metallicities for the three clusters of [Fe/H]=−0.68, −0.57 and −0.90, respectively. These updated ages and metallicities are in good agreement with the age-metallicity relation for the bulk of SMC clusters. Total cluster masses ranging from ∼7-11×10^3 $M_\odot$ were estimated from integrated flux, consistent with masses estimated for other SMC clusters of similar ages. These results reduce the number of SMC clusters known to be older than about 5 Gyr and highlight the need of deep and spatially resolved photometry to determine accurate ages for older, low-luminosity SMC star clusters.

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A *Gaia* EDR3 search for tidal tails in disintegrating open clusters

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We carry out a search for tidal tails in a sample of open clusters with known relatively elongated morphology. We identify the member stars of these clusters from the precise astrometric and deep photometric data from *Gaia* Early Data Release 3 using the robust membership determination algorithm, ML-MOC. We identify 46 open clusters having a stellar corona beyond the tidal radius, 20 of which exhibit extended tails aligned with the cluster orbit direction in galactocentric coordinates. Notably we find NGC 6940 (at a distance of ∼ 1 kpc) is the furthest open cluster exhibiting tidal tails that are ∼ 50 pc from its center, while also identifying ∼ 40 pc long tidal tails for the nearby Pleiades. Using the minimum spanning tree length for the most massive stars relative to all cluster members, we obtain the mass segregation ratio (λ_{MSR}) profiles as a function of the number of massive stars in each cluster. From these profiles, we can classify the open clusters into four classes based on the degree of mass segregation experienced by the clusters. We find that clusters in the most mass segregated classes are the oldest on average and have the flattest mass function slope. Of the 46 open clusters studied in this work, 41 exhibit some degree of mass segregation. Furthermore, we estimate the initial masses (M_i) of these open clusters finding that some of them, having $M_i \gtrsim 10^4 M_\odot$, could be the dissolving remnants of Young Massive Clusters.

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Assessing the physical reality of Milky Way open cluster candidates

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We report results on the analysis of eleven new Milky Way open cluster candidates, recently discovered from the detection of stellar overdensities in the Vector Point diagram, by employing extreme deconvolution Gaussian mixture models. We treated these objects as real open clusters and derived their fundamental properties with their associated intrinsic dispersions by exploring the parameter space through the minimization of likelihood functions on generated synthetic colour-magnitude diagrams (CMDs). The intrinsic dispersions of the resulting ages turned out to be much larger than those usually obtained for open clusters. Indeed, they resemble those of ages and metallicities of composite star field populations. We also traced their stellar number density profiles and mass functions, derived their total masses, Jacobi and tidal radii, which helped us as criteria while assessing their physical nature as real open clusters. Because the eleven candidates show a clear gathering of stars in the proper motion plane and some hint for similar distances, we concluded that they are possibly sparse groups of stars.

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Small Magellanic Cloud field stars meddling in star cluster age estimates

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I revisited the age of the Small Magellanic Cloud cluster HW 42, whose previous estimates differ in more than 6 Gyr, thus challenging the most updated knowledge of the SMC star formation history. I performed an analysis of number stellar density profiles at different brightness levels; carried out a field star decontamination of the cluster color-magnitude diagram; and estimated the cluster fundamental parameters from the minimization of likelihood functions and their uncertainties from standard bootstrap methods. I conclude that HW 42 is a $6.2^{+1.6}_{-1.3}$ Gyr old ([Fe/H] = $-0.89^{+0.10}_{-0.11}$ dex) SMC cluster projected on to a SMC composite star field population which shows variations in magnitude, color, and stellar density of Main Sequence stars. The present outcome solves the conundrum of the previous age discrepancies and moves HW 42 to a region in the SMC age-metallicity relationship populated by star clusters.

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Photometry of the Four Anti-Galactocentric Old Open Clusters: Czernik 30, Berkeley 34, Berkeley 75, and Berkeley 76

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We present a BVI photometric study of four old open clusters (OCs) in the Milky Way Galaxy, Czernik 30, Berkeley 34, Berkeley 75, and Berkeley 76 using the observation data obtained with the SMARTS 1.0 m telescope at the CTIO, Chile. These four OCs are located at the anti-Galactocentric direction and in the Galactic plane. We determine the fundamental physical parameters for the four OCs, such as age, metallicity, distance modulus, and color excess, using red clump and PARSEC isochrone fitting methods after finding center and size of the four OCs. These four old OCs are 2-3 Gyr old and 6-8 kpc away from the Sun. The metallicity ([Fe/H]) values of the four OCs are between -0.6 and 0.0 dex. We combine data for these four OCs with those for old OCs from five literatures resulting in 236 objects to investigate Galactic radial metallicity distribution. The gradient of a single linear fit for this Galactocentric [Fe/H] distribution is -0.052 ± 0.004 dex/kpc. If we assume the existence of a discontinuity in this radial metallicity distribution, the gradient at Galactocentric radius < 12 kpc is -0.070 ± 0.006 dex/kpc, while that at the outer part is -0.016 ± 0.010 which is flatter than that of the inner part. Although there are not many sample clusters at the outer part, the broken linear fit seems to better follow the observation data.

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CLusters in the Uv as EngineS (CLUES): I. Survey presentation & FUV spectral analysis of the stellar light

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The CLusters in the Uv as EngineS (CLUES) survey is a Cosmic Origins Spectrograph (COS) campaign aimed at acquiring the 1130 to 1770 Å, restframe spectroscopy of very young (<20 Myr) and massive ($>10^4$ solar masses) star clusters in galaxies that are part of the Hubble treasury program Legacy ExtraGalactic Uv Survey (LEGUS). In this first paper of a series, we describe the CLUES sample consisting of 20 young star clusters and report their physical properties as derived by both multi-wavelength photometry and far-UV (FUV) spectroscopy with Hubble Space Telescope (HST). Thanks to the synergy of the two different datasets we build a coherent picture of the diverse stellar populations found in each region (with sizes of 40 to 160 pc). We associate the FUV-brightest stellar population to the central targeted star cluster and the other modeled population to the diffuse stars that are included in the COS aperture. We observe better agreement between photometric and spectroscopic ages for star clusters younger than 5 Myr. For clusters older than 5 Myr, photometry and spectroscopy measurements deviate, with the latter producing older ages, due to the degeneracy of photometric models. FUV spectroscopy enables us to better constrain the stellar metallicities, a parameter that optical colors are insensitive to. Finally, the derived E(B-V) are quite similar, with a tendency for FUV spectroscopy to favor solutions with higher extinctions. The recovered masses are in agreement within a factor of 2 for all the clusters.

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Star cluster populations in the local universe

Integrated Mass Loss of Evolved Stars in M4 using Asteroseismology

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Mass loss remains a major uncertainty in stellar modelling. In low-mass stars, mass loss is most significant on the red giant branch (RGB), and will impact the star's evolutionary path and final stellar remnant. Directly measuring the mass difference of stars in various phases of evolution represents one of the best ways to quantify integrated mass loss. Globular clusters (GCs) are ideal objects for this. M4 is currently the only GC for which asteroseismic data exists for stars in multiple phases of evolution. Using K2 photometry, we report asteroseismic masses for 75 red giants in M4, the largest seismic sample in a GC to date. We find an integrated RGB mass loss of $\Delta\bar{M} = 0.17 \pm 0.01$ $M_{\odot}$, equivalent to a Reimers' mass-loss coefficient of $\eta_R = 0.39$. Our results for initial mass, horizontal branch mass, η_R, and integrated RGB mass loss show remarkable agreement with previous studies, but with higher precision using asteroseismology. We also report the first detections of solar-like oscillations in early asymptotic giant branch (EAGB) stars in GCs. We find an average mass of $\bar{M}_{\rm EAGB} = 0.54 \pm 0.01$ $M_{\odot}$, significantly lower than predicted by models. This suggests larger-than-expected mass loss on the horizontal branch. Alternatively, it could indicate unknown systematics in seismic scaling relations for the EAGB. We discover a tentative mass bi-modality in the RGB sample, possibly due to the multiple populations. In our red horizontal branch sample, we find a mass distribution consistent with a single value. We emphasise the importance of seismic studies of GCs since they could potentially resolve major uncertainties in stellar theory.

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UOCSVIII. UV Study of the open cluster NGC 2506 using ASTROSAT

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We study an intermediate-age open cluster (OC) NGC 2506 using the ASTROSAT/UVIT data and other archival data. We identified 2175 cluster members using a machine learning-based algorithm, ML-MOC, on Gaia EDR3 data. Among the cluster members detected in UVIT filters, F148W, F154W, and F169M, we detect nine blue straggler stars (BSS), three yellow straggler stars (YSS), and three red clump (RC) stars. We construct multiwavelength spectral energy distributions (SEDs) of these objects to characterize them and to estimate their parameters. We discovered hot companions to three BSS, two YSS, and three RC candidates and estimated their properties. The hot companions with estimated temperatures, Teff $\sim$ 13250-31000 K, are WDs of extremely low mass (ELM, $\sim$ 0.20 $M_{\odot}$), low mass (LM, $\sim$ 0.20-0.40 $M_{\odot}$), normal mass ($\sim$ 0.40-0.60 $M_{\odot}$), and high mass ($\sim$ 0.8 $M_{\odot}$). We suggest that systems with ELM and LM WDs as companions are formed via Case-A/Case-B mass transfer mechanism. A BSS is the likely progenitor of the high-mass WD, as a star with more than the turn-off mass of the cluster is needed to form a high-mass WD. Thus, systems with a high-mass WD are likely to be formed through merger in triple systems. We conclude that mass transfer as well as merger pathways of BSS formation are present in this cluster.

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Chemically Peculiar Stars in the Open Cluster Stock 2

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The recently re-discovered open cluster Stock 2, located roughly 375 pc away and about 400 Myr old, has the potential to be an exciting new testbed for our understanding of stellar evolution. We present results from a spectroscopic campaign to characterize stars near the cluster's main-sequence turnoff; our goal is to identify candidate chemically peculiar stars among the cluster's A stars. We obtained echelle spectra for 64 cluster members with ESPaDOnS on the 3.6-m Canada-France-Hawaii Telescope, Mauna Kea Observatory, USA, and for six stars with SOPHIE on the 1.93-m telescope at the Observatoire de Haute-Provence, France. We complemented these new observations with those of 13 high-mass cluster members from the HARPS-N archive; our overall sample is of 71 stars. We derived the fundamental parameters (Teff, log g, [M/H]) as well as vsini for our sample using the Sliced Inverse Regression (SIR) technique, and then used iSpec to derive individual abundances of 12 chemical species. With these abundance determinations, we identified nine A stars with anomalous levels of Sc, Ca, and other metallic lines. Follow-up observations of these Am candidates with a known age can transform them into benchmarks for evolutionary models that include atomic diffusion and help build a better understanding of the complex interactions between macroscopic and microscopic processes in stellar interiors.

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Multiple stellar populations in the high-temperature regime: Potassium abundances in the globular cluster M 54 (NGC 6715)

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Among the multiple stellar populations in globular clusters (GCs) the very high-temperature H-burning regime, able to produce elements up to potassium, is still poorly explored. Here we present the first abundance analysis of K in 42 giants of NGC 6715 (M 54) with homogeneous abundances of light elements previously derived in our FLAMES survey. Owing to the large mass and low metallicity, a large excess of K could be expected in this GC, which is located in the nucleus of the Sagittarius dwarf galaxy. We actually found a spread in [K/Fe] spanning about 1 dex, with [K/Fe] presenting a significant anti-correlation with [O/Fe] ratios, regardless of the metallicity component in M 54. Evidence for a K-Mg anti-correlation also exists, but this is statistically marginal because of the lack of very Mg-poor stars in this GC. We found, however, a strong correlation between K and Ca. These observations clearly show that the K enhancement in M 54 is probably due to the same network of nuclear reactions generating the phenomenon of multiple stellar populations, at work in a regime of very high temperature. The comparison with recent results in omega Cen is hampered by an unexplained trend with the temperatures for K abundances from optical spectroscopy, and somewhat by a limited sample size for infrared APOGEE data. There are few doubts, however, that the two most massive GCs in the Milky Way host a K-Mg anti-correlation.

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On the validity of the spectroscopic age indicators [Y/Mg], [Y/Al], [Y/Si], [Y/Ca], and [Y/Ti] for giant stars

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The abundance ratios [Y/Mg], [Y/Al], [Y/Si], [Y/Ca], and [Y/Ti] have been suggested as chemical clocks for solar-metallicity dwarf stars in the field as well as for giant stars in open clusters. To verify this last hypothesis, we derive these abundances ratios of 50 giant stars belonging to seven open clusters. To calculate the abundances, we analyze FEROS spectra assuming the LTE-hypothesis. We confirm that [Y/Mg], [Y/Al], [Y/Si], [Y/Ca], and [Y/Ti] work as chemical clocks for field dwarf stars at the local region (d $<$ 1 kpc) whereas for the field giants the [Y/Mg], [Y/Al] and [Y/Si] also present trends with the ages but high scattering. [Y/Ca] and [Y/Ti] do not present any correlation with ages in the field giants. In Our open clusters, the behaviour is similar, [Y/Mg], [Y/Al] and [Y/Si] present evident trends, whereas [Y/Ca] vs. Ages is a flat and [Y/Ti] vs. Ages is less steep. We also confirm that the chemical clocks have high scatter at the early ages. In the case of the compiled sample, the chemical clocks are similar to our results but in some situations there are important differences. Several relations between abundance ratios and ages may be obtained when dwarfs and giants are analyzed, confirming the non-universality of the spectroscopic age indicators.

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Discovery of double BSS sequences in the old Galactic open cluster Berkeley 17

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Blue straggler stars (BSS) are peculiar objects which normally appear as a single broad sequence along the extension of the main sequence. Only four globular clusters (GCs) have been observed to have two distinct and parallel BSS sequences. For the first time for any open cluster (OC), we report double BSS sequences in Berkeley 17. Using the machine-learning based membership algorithm ML-MOC on Gaia EDR3 data, we identify 627 cluster members, including 21 BSS candidates out to 15' from the cluster center. Both the BSS sequences are almost equally populated and parallel to one another in Gaia as well as in Pan-STARRS colour-magnitude diagram (CMD). We statistically confirm their presence and report that both BSS sequences are highly segregated compared to the reference population out to ∼5.5' and not segregated thereafter. The lower densities of OCs make BSS formation impossible via the collisional channel. Therefore, mass transfer seems to be the only viable channel for forming candidates of both sequences. The gap between the red and blue BSS sequences, on the other hand, is significant and presents a great opportunity to understand the connection between BSS formation and internal as well as external dynamics of the parent clusters.

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Evolved Eclipsing Binaries and the Age of the Open Cluster NGC 752

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We present analyses of improved photometric and spectroscopic observations for two detached eclipsing binaries at the turnoff of the open cluster NGC 752: the 1.01 day binary DS And and the 15.53 d BD +37 410. For DS And, we find $M_1 = 1.692 \pm 0.004 \pm 0.010 M_\odot$, $R_1 = 2.185 \pm 0.004 \pm 0.008 R_\odot$, $M_2 = 1.184 \pm 0.001 \pm 0.003 M_\odot$, and $R_2 = 1.200 \pm 0.003 \pm 0.005 R_\odot$. We either confirm or newly identify unusual characteristics of both stars in the binary: the primary star is found to be slightly hotter than the main sequence turn off and there is a more substantial discrepancy in its luminosity compared to models (model luminosities are too large by about 40%), while the secondary star is oversized and cooler compared to other main sequence stars in the same cluster. The evidence points to non-standard evolution for both stars, but most plausible paths cannot explain the low luminosity of the primary star. BD +37 410 only has one eclipse per cycle, but extensive spectroscopic observations and the TESS light curve constrain the stellar masses well: $M_1 = 1.717 \pm 0.011 M_\odot$ and $M_2 = 1.175 \pm 0.005 M_\odot$. The radius of the main sequence primary star near $2.9 R_\odot$ definitively requires large convective core overshooting (> 0.2 pressure scale heights) in models for its mass, and multiple lines of evidence point toward an age of $1.61 \pm 0.03 \pm 0.05$ Gyr (statistical and systematic uncertainties). Because NGC 752 is currently undergoing the transition from non-degenerate to degenerate He ignition of its red clump stars, BD +37 410 A directly constrains the star mass where this transition occurs.

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Demographics of the M-star Multiple Population in the Orion Nebula Cluster

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We present updated results constraining multiplicity demographics for the stellar population of the Orion Nebula Cluster (ONC, a high-mass, high-density star-forming region), across primary masses 0.08-0.7$M_{\odot}$. Our study utilizes archival Hubble Space Telescope data obtained with the Advanced Camera for Surveys using multiple filters (GO-10246). Previous multiplicity surveys in low-mass, low-density associations like Taurus identify an excess of companions to low-mass stars roughly twice that of the Galactic field and find the mass ratio distribution consistent with the field. Previously, we found the companion frequency to low-mass stars in the ONC is consistent with the Galactic field over mass ratios=0.6-1.0 and projected separations=30-160au, without placing constraints on the mass ratio distribution. In this study, we investigate the companion population of the ONC with a double point-spread function (PSF) fitting algorithm sensitive to separations larger than 10au (0.025") using empirical PSF models. We identified 44 companions (14 new), and with a Bayesian analysis, estimate the companion frequency to low-mass stars in the ONC $=0.13^{+0.05}_{-0.03}$ and the power law fit index to the mass ratio distribution $=2.08^{+1.03}_{-0.85}$ over all mass ratios and projected separations of 10-200au. We find the companion frequency in the ONC is consistent with the Galactic field population, likely from high transient stellar density states, and a probability of 0.002 that it is consistent with that of Taurus. We also find the ONC mass ratio distribution is consistent with the field and Taurus, potentially indicative of its primordial nature, a direct outcome of the star formation process.

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Star clusters at high redshift

Star formation at the smallest scales; A JWST study of the clump populations in SMACS0723

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We present the clump populations detected in 18 lensed galaxies at redshifts 1 to 8.5 within the lensing cluster field SMACS0723. The recent JWST Early Release Observations of this poorly known region of the sky have revealed numerous point-like sources within and surrounding their host galaxies, undetected in the shallower HST images. We use JWST multiband photometry and the lensing model of this galaxy cluster to estimate the intrinsic sizes and magnitudes of the stellar clumps. We derive optical restframe effective radii from <10 to 100s pc and masses ranging from 10^5 to 10^9 $M_\odot$, overlapping with massive star clusters in the local universe. The ages range from 1 Myr to 1 Gyr. We compare the crossing time to the age of the clumps and determine that between 45 and 60 % of the detected clumps are consistent with being gravitationally bound. The lack of Gyr old clumps suggest that the dissolution time scales are shorter than 1 Gyr. We see a significant increase in the luminosity (mass) surface density of the clumps with redshift. Clumps in galaxies at the reionisation era have stellar densities higher than massive clusters in the local universe. We zoom-in into single galaxies at redshift <6 and find for two galaxies, the Sparkler and the Firework, that their star clusters/clumps show distinctive colour distributions and location surrounding their host galaxy that are compatible with being accredited or formed during merger events. The ages of some of the compact clusters are between 1 and 4 Gyr, e.g., globular cluster precursors formed around 9-12 Gyr ago. Our study, conducted on a small sample of galaxies, shows the potential of JWST observations for understanding the conditions under which star clusters form in rapidly evolving galaxies.

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JWST/NIRCam Probes Young Star Clusters in the Reionization Era Sunrise Arc

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Star cluster formation in the early universe and their contribution to reionization remains to date largely unconstrained. Here we present JWST/NIRCam imaging of the most highly magnified galaxy known at z $\sim$ 6, the Sunrise arc. We identify six young massive star clusters (YMCs) with measured radii spanning $\sim$ 20 pc down to $\sim$ 1 pc (corrected for lensing magnification), estimated stellar masses of $\sim 10^{(6-7)}$ $M_\odot$, and with ages 1-30 Myr based on SED fitting to photometry measured in 8 filters extending to rest-frame 7000Å. The resulting stellar mass surface densities are higher than 1000 $M_\odot$ pc^{-2} (up to a few 10^5 $M_\odot$ pc^{-2}) and their inferred dynamical ages qualify the majority of these systems as gravitationally-bound stellar clusters. The star cluster ages map the progression of star formation along the arc, with to evolved systems ($\gtrsim$ 10 Myr old) followed by very young clusters. The youngest stellar clusters ($<$ 5 Myr) show evidence of prominent Hbeta + [OIII]4959,5007 emission, based on photometry, with equivalent widths larger than 1000 A rest-frame, and are hosted in a 200 pc sized star-forming complex. Such a region dominates the ionizing photon production, with a high efficiency $\log(\xi_{ion}$ [Hz erg^{-1}]) $\sim$ 25.7. A significant fraction of the recently formed stellar mass of the galaxy ($>$ 10-30 %) occurred in these YMCs. We speculate that such sources of ionizing radiation boost the ionizing photon production efficiency which eventually carve ionized channels that might favor the escape of Lyman continuum radiation. The survival of some of the clusters would make them the progenitors of massive and relatively metal-poor globular clusters in the local Universe.

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Early results from GLASS-JWST. VII: evidence for lensed, gravitationally bound proto-globular clusters at z=4 in the Hubble Frontier Field A2744

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We investigate the blue and optical rest-frame sizes ($\lambda \sim$ 2300Å-4000Å) of three compact star-forming regions in a galaxy at z=4 strongly lensed (x30, x45, x100) by the Hubble Frontier Field galaxy cluster A2744 using GLASS-ERS JWST/NIRISS imaging at 1.15μm, 1.50μm and 2.0μm with PSF $\lesssim$ 0.1". In particular, the Balmer break is probed in detail for all multiply-imaged sources of the system. With ages of a few tens of Myr, stellar masses in the range (0.7-4.0) $\times$ 10^6 $M_\odot$ and optical/ultraviolet effective radii spanning the interval $3 < R_{eff} < 20$ pc, such objects are currently the highest redshift (spectroscopically-confirmed) gravitationally-bound young massive star clusters (YMCs), with stellar mass surface densities resembling those of local globular clusters. Optical (4000Å, JWST-based) and ultraviolet (1600Å, HST-based) sizes are fully compatible. The contribution to the ultraviolet underlying continuum emission (1600Å) is ∼30%, which decreases by a factor of two in the optical for two of the YMCs (∼4000Å rest-frame), reflecting the young ages (<30 Myr) inferred from the SED fitting and supported by the presence of high-ionization lines secured with VLT/MUSE. Such bursty forming regions enhance the sSFR of the galaxy, which is ∼10 Gyr^{-1}. This galaxy would be among the extreme analogs observed in the local Universe having high star formation rate surface density and high occurrence of massive stellar clusters in formation.

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Simulation formation/evolution of cluster populations

Ionising Feedback Effects on Star Formation in Globular Clusters with Multiple Stellar Populations

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Using 3D radiation-hydrodynamical simulations, we study the effects of ionising radiation on the formation of second-generation (SG) stars in Globular Clusters (GCs) with multiple stellar populations. In particular, we focus on massive ($10^7 M_\odot$) and young (40-Myr old) GCs. We consider stellar winds from asymptotic giant branch (AGB) stars, ram pressure, gas accretion onto the cluster, and photoionisation feedback of binary stars. We find that the stellar luminosity is strong enough to warm and ionise the intracluster medium, but it does not lead to a significant gas expulsion. The cluster can thus retain the ejecta of AGB stars and the accreted pristine gas. In addition, efficient cooling occurs in the central region of the cluster within 50Myr from the formation of first generation stars, leading to the formation of SG stars. Our results indicate that the inclusion of photoionisation does not suppress SG formation, but rather delays it by about $\sim$ 10Myr. The time delay depends on the density of the pristine gas, so that a denser medium exhibits a shorter delay in star formation. Moreover, photoionisation leads to a modest decrease in the total SG mass, compared to a model without it.

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The role of rotation on the formation of second generation stars in globular clusters

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By means of 3D hydrodynamic simulations, we explore the effects of rotation in the formation of second-generation (SG) stars in globular clusters (GC). Our simulations follow the SG formation in a first-generation (FG) internally rotating GC; SG stars form out of FG asymptotic giant branch (AGB) ejecta and external pristine gas accreted by the system. We have explored two different initial rotational velocity profiles for the FG cluster and two different inclinations of the rotational axis with respect to the direction of motion of the external infalling gas, whose density has also been varied. For a low (10^{-24} g cm^{-3}) external gas density, a disk of SG helium-enhanced stars is formed. The SG is characterized by distinct chemo-dynamical phase space patterns: it shows a more rapid rotation than the FG with the helium-enhanced SG subsystem rotating more rapidly than the moderate helium-enhanced one. In models with high external gas density (10^{-23} g cm^{-3}), the inner SG disc is disrupted by the early arrival of external gas and only a small fraction of highly enhanced helium stars preserves the rotation acquired at birth. Variations in the inclination angle between the rotation axis and the direction of the infalling gas and the velocity profile can slightly alter the extent of the stellar disc and the rotational amplitude. No significant variation has been found in the timespan of our simulations when changing the inclination angle between the rotation axis and the direction of the infalling gas, while different velocity profiles can slightly alter the extent of the stellar disc and the rotational amplitude. The results of our simulations illustrate the complex link between dynamical and chemical properties of multiple populations and provide new elements for the interpretation of observational studies and future investigations of the dynamics of multiple-population GCs.

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Simulation star cluster formation/dynamical evolution

Introducing EMP-Pathfinder: modelling the simultaneous formation and evolution of stellar clusters in their host galaxies

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The formation and evolution of stellar clusters is intimately linked to that of their host galaxies. To study this connection, we present the EMP-Pathfinder suite of cosmological zoom-in Milky Way-mass simulations. These simulations contain a sub-grid description for stellar cluster formation and evolution, allowing us to study the simultaneous formation and evolution of stellar clusters alongside their host galaxies across cosmic time. As a key ingredient in these simulations, we include the physics of the multi-phase nature of the interstellar medium (ISM), which enables studies of how the presence of a cold, dense ISM affects cluster formation and evolution. We consider two different star formation prescriptions: a constant star formation efficiency per free-fall time, as well as an environmentally-dependent, turbulence-based prescription. We identify two key results drawn from these simulations. Firstly, we find that tidal shock-driven disruption caused by the graininess of the cold ISM produces old ($\tau > 10$ Gyr) stellar cluster populations with properties that are in excellent agreement with the observed populations in the Milky Way and M31. Importantly, the addition of the cold ISM addresses the areas of disagreement found in previous simulations that lacked the cold gas phase. Secondly, the formation of stellar clusters is extremely sensitive to the baryonic physics that govern the properties of the cold, dense gas reservoir in the galaxy. This implies that the demographics of stellar cluster populations represent an important diagnostic tool for constraining baryonic physics models in upcoming galaxy formation simulations that also include a description of the cold ISM.

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Asymmetrical tidal tails of open star clusters: stars crossing their cluster's práh challenge Newtonian gravitation

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After their birth a significant fraction of all stars pass through the tidal threshold (prah) of their cluster of origin into the classical tidal tails. The asymmetry between the number of stars in the leading and trailing tails tests gravitational theory. All five open clusters with tail data (Hyades, Praesepe, Coma Berenices, COIN-Gaia 13, NGC 752) have visibly more stars within $d_{cl} = 50$ pc of their centre in their leading than their trailing tail. Using the Jerabkova-compact-convergent-point (CCP) method, the extended tails have been mapped out for four nearby 600-2000 Myr old open clusters to $d_{cl} > 50$ pc. These are on near-circular Galactocentric orbits, a formula for estimating the orbital eccentricity of an open cluster being derived. Applying the Phantom of Ramses code to this problem, in Newtonian gravitation the tails are near-symmetrical. In Milgromian dynamics (MOND) the asymmetry reaches the observed values for $50 < d_{cl}/\mathrm{pc} < 200$, being maximal near peri-galacticon, and can slightly invert near apo-galacticon, and the Küpper epicyclic overdensities are asymmetrically spaced. Clusters on circular orbits develop orbital eccentricity due to the asymmetrical spill-out, therewith spinning up opposite to their orbital angular momentum. This positive dynamical feedback suggests Milgromian open clusters to demise rapidly as their orbital eccentricity keeps increasing. Future work is necessary to better delineate the tidal tails around open clusters of different ages and to develop a Milgromian direct n-body code.

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Miscellaneous

Constraining the shape of dark matter haloes with globular clusters

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We explore how diffuse stellar light and globular clusters (GCs) can be used to trace the matter distribution of their host halo using an observational methodology. For this, we use 117 simulated dark matter (DM) haloes from the $(34.4\ \mathrm{cMpc})^3$ periodic volume of the E-MOSAICS project. For each halo, we compare the stellar surface brightness and GC projected number density maps to the surface densities of DM and total mass. We find that the dominant structures identified in the stellar light and in the GCs correspond closely with those from the DM and total mass. Our method is unaffected by the presence of satellites and its precision improves with fainter GC samples. We recover tight relations between the profiles of stellar surface brightness and GC number density to those of the DM, suggesting that the profile of DM can be accurately recovered from the stars and GCs ($\sigma \leq 0.5$ dex). We quantify the projected morphology of DM, stars and GCs, and find that the stars and GCs are more flattened than the DM. Additionally, the semi-major axes of the distribution of stars and GCs are typically misaligned by ~ 10 degrees from that of DM. We demonstrate that deep imaging of diffuse stellar light and GCs can place constraints on the shape, profile and orientation of their host halo. These results extend down to haloes with central galaxies $M_\star \geq 10^{10}\ M_\odot$, and the analysis will be applicable to future data from the Euclid, Roman and the Rubin observatories.

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The relation between globular cluster systems and supermassive black holes in spiral galaxies III. The link to the $M_\bullet - M_*$ correlation

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We continue to explore the relationship between globular cluster total number, $N_{\rm GC}$, and central black hole mass, $M_\bullet$, in spiral galaxies. We present here results for the Sab galaxies NGC 3368, NGC 4736 (M 94) and NGC 4826 (M 64), and the Sm galaxy NGC 4395. The globular cluster (GC) candidate selection is based on the (u^* - i') versus (i' - K_s) color-color diagram, and i'-band shape parameters. We determine the $M_\bullet$ versus $N_{\rm GC}$ correlation for these spirals, plus NGC 4258, NGC 253, M 104, M 81, M 31, and the Milky Way. We also redetermine the correlation for the elliptical sample in Harris, Poole, & Harris (2014), with updated galaxy types from Sahu et al. 2019b. Additionally, we derive total stellar galaxy mass, M_*, from its two-slope correlation with $N_{\rm GC}$ (Hudson, Harris, & Harris 2014), and fit $M_\bullet$ versus M_* for both spirals and ellipticals. We obtain log $M_\bullet \propto$ (1.01 $\pm$ 0.13) log $N_{\rm GC}$ for ellipticals, and log $M_\bullet \propto$ (1.64 $\pm$ 0.24) log $N_{\rm GC}$ for late type galaxies (LTG). The linear $M_\bullet$ versus $N_{\rm GC}$ correlation in ellipticals could be due to statistical convergence through mergers, but not the much steeper correlation for LTG. However, in the $M_\bullet$ versus total stellar mass (M_*) parameter space, with M_* derived from its correlation with $N_{\rm GC}$, $M_\bullet \propto$ (1.48 $\pm$ 0.18) log M_* for ellipticals, and $M_\bullet \propto$ (1.21 $\pm$ 0.16) log M_* for LTG. The observed agreement between ellipticals and LTG in this parameter space may imply that black holes and galaxies co-evolve through "calm" accretion, AGN feedback, and other secular processes.

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Ph.D. (dissertation) summaries

Panchromatic study of star clusters: binaries, blue lurkers, blue stragglers and membership

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Binary systems can evolve into immensely different exotic systems such as blue straggle stars (BSSs), yellow straggler stars, cataclysmic variables, type Ia supernovae depending on their initial mass, the orbital parameters and evolution. The aim of this thesis is to understand the demographics of post-mass-transfer systems (BSSs, white dwarfs and blue lurkers) present in the open clusters and how they are formed. First, we identified the cluster members using Gaia EDR3 data in six open clusters. Two of the clusters, M67 and King2, were studied in detail using UVIT, Gaia, GALEX, 2MASS and other archival photometric data. The comprehensive panchromatic study showed that (i) there is a robust mass-transfer pathway for BSSs, and blue lurkers in M67, (ii) at least 15% of BSSs in King 2 were formed via binary mass transfer. We also created a homogeneous catalogue of open cluster BSSs using Gaia DR2 data. The analysis of 868 BSSs across 208 clusters showed that (i) BSS frequency increases with age, (ii) there is a power-law relation between cluster mass and maximum number of BSSs, (iii) the formation mechanism of BSSs is dominated by binary mass transfer (54-67%) though there exists a 10-16% chance of BSSs forming through more than 2 stellar interactions. This study demonstrates that there exists an extensive variety in the demographics of binary products, and the UV observations are vital for their detection and characterisation.

PhD thesis completed at the Indian Institute of Science under the supervision of Prof. Annapurni Subramaniam.
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