THE MAGELLANIC CLOUDS NEWSLETTER

An electronic publication dedicated to the Magellanic Clouds, and astrophysical phenomena therein

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Editor: Jacco van Loon

Editorial

Dear Colleagues,

It is my pleasure to present you the 179th issue of the Magellanic Clouds Newsletter. There's a lot on the interstellar medium and star clusters, as well as massive stars.

We are fortunate to be in such privileged position to study the Magellanic Clouds. It could have been so different. We could have lived three billion years ago, or three billion years from now... or in the Andromeda galaxy instead. Or we could have lived in the slums of a metropolis.

Pictures for the front page remain welcome, just e-mail astro.mcnews@keele.ac.uk.

The next issue is hoped to be distributed on the 1st of December.

Editorially Yours,
Jacco van Loon

GASKAP-HI pilot survey science – III: An unbiased view of cold gas in the Small Magellanic Cloud

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We present the first unbiased survey of neutral hydrogen (H I) absorption in the Small Magellanic Cloud (SMC). The survey utilises pilot H I observations with the Australian Square Kilometre Array Pathfinder (ASKAP) telescope as part of the Galactic ASKAP H I (GASKAP-HI) project whose dataset has been processed with the GASKAP-HI absorption pipeline, also described here. This dataset provides absorption spectra towards 229 continuum sources, a 275% increase in the number of continuum sources previously published in the SMC region, as well as an improvement in the quality of absorption spectra over previous surveys of the SMC. Our unbiased view, combined with the closely matched beam size between emission and absorption, reveals a lower cold gas faction (11%) than the 2019 ATCA survey of the SMC and is more representative of the SMC as a whole. We also find that the optical depth varies greatly between the SMC's bar and wing regions. In the bar we find that the optical depth is generally low (correction factor to the optically thin column density assumption of $R_{\rm HI} \sim 1.04$) but increases linearly with column density. In the wing however, there is a wide scatter in optical depth despite a tighter range of column densities.

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METAL: The Metal Evolution, Transport, and Abundance in the Large Magellanic Cloud *Hubble* program – III. Interstellar depletions, dust-to-metal, and dust-to-gas ratios versus metallicity

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The metallicity and gas density dependence of interstellar depletions, the dust-to-gas (D/G), and dust-to-metal (D/M) ratios have important implications for how accurately we can trace the chemical enrichment of the universe; either by using FIR dust emission as a tracer of the ISM; or by using spectroscopy of damped Lyman-α systems (DLAs) to measure chemical abundances over a wide range of redshifts. We collect and compare large samples of depletion measurements in the Milky Way (MW), LMC ($Z = 0.5$ $Z_\odot$), and SMC ($Z = 0.2$ $Z_\odot$). The relation between the depletions of different elements do not strongly vary between the three galaxies, implying that abundance ratios should trace depletions accurately down to 20% solar metallicity. From the depletions, we derive D/G and D/M. The D/G increases with density, consistent with the more efficient accretion of gas-phase metals onto dust grains in the denser ISM. For $\log N(\mathrm{H}) > 21$ cm^{-2}, the depletion of metallicity tracers (S, Zn) exceeds -0.5 dex, even at 20% solar metallicity. The gas fraction of metals increases from the MW to the LMC (factor 3) and SMC (factor 6), compensating the reduction in total heavy element abundances and resulting in those three galaxies having the same neutral gas-phase metallicities. The D/G derived from depletions are a factor of 2 (LMC) and 5 (SMC) higher than the D/G derived from FIR, 21-cm, and CO emission, likely due to the combined uncertainties on the dust FIR opacity and on the depletion of carbon and oxygen.

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Structural and dynamical analysis of the quiescent Molecular Ridge in the Large Magellanic Cloud

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We present a comparison of low-J ^{13}CO and CS observations of four different regions in the LMC – the quiescent Molecular Ridge, 30 Doradus, N 159, and N 113, all at a resolution of ~ 3 pc. The regions 30 Dor, N 159, and

N 113 are actively forming massive stars, while the Molecular Ridge is forming almost no massive stars, despite its large reservoir of molecular gas and proximity to N 159 and 30 Dor. We segment the emission from each region into hierarchical structures using dendrograms and analyze the sizes, masses, and linewidths of these structures. We find that the Ridge has significantly lower kinetic energy at a given size scale and also lower surface densities than the other regions, resulting in higher virial parameters. This suggests that the Ridge is not forming massive stars as actively as the other regions because it has less dense gas and not because collapse is suppressed by excess kinetic energy. We also find that these physical conditions and energy balance vary significantly within the Ridge and that this variation appears only weakly correlated with distance from sites of massive star formation such as R 136 in 30 Dor, which is ~ 1 kpc away. These variations also show only a weak correlation with local star formation activity within the clouds.

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Evidence of globular cluster abundance anomalies in the SMC intermediate-age cluster Kron 3

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Using spectra obtained with the VLT/FORS2 and Gemini-S/GMOS-S instruments, we have investigated carbon, nitrogen and sodium abundances in a sample of red giant members of the Small Magellanic Cloud star cluster Kron 3. The metallicity and luminosity of the cluster are comparable to those of Galactic globular clusters but it is notably younger (age ≈ 6.5 Gyr). We have measured the strengths of the CN and CH molecular bands, finding a bimodal CN band-strength distribution and a CH/CN anti-correlation. Application of spectrum synthesis techniques reveals that the difference in the mean [N/Fe] and [C/Fe] values for the CN-strong and CN-weak stars are $\Delta\langle[\mathrm{N/Fe}]\rangle = 0.63 \pm 0.16$ dex and $\Delta\langle[\mathrm{C/Fe}]\rangle = -0.01 \pm 0.07$ dex after applying corrections for evolutionary mixing. We have also measured sodium abundances from the Na D lines finding an observed range in [Na/Fe] of ~ 0.6 dex that correlates positively with the [N/Fe] values and a $\Delta\langle[\mathrm{Na/Fe}]\rangle = 0.12 \pm 0.12$ dex. While the statistical significance of the sodium abundance difference is not high, the observed correlation between the Na and N abundances supports its existence. The outcome represents the first star-by-star demonstration of correlated abundance variations involving sodium in an intermediate-age star cluster. The results add to existing photometric and spectroscopic indications of the presence of multiple populations in intermediate-age clusters with masses in excess of $\sim 10^5$ $M_\odot$. It confirms that the mechanism(s) responsible for the multiple populations in ancient globular clusters cannot solely be an early cosmological effect applying only in old clusters.

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Wind properties of Milky Way and SMC massive stars: empirical Z dependence from CMFGEN models

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Detailed knowledge about stellar winds and evolution at different metallicities is crucial for understanding stellar populations and feedback in the Local Group of galaxies and beyond. Despite efforts in the literature, we still lack a comprehensive, empirical view of the dependence of wind properties on metallicity (Z). Here, we investigate the winds of O and B stars in the Milky Way (MW) and Small Magellanic Cloud (SMC). We gathered a sample of 96 stars analyzed by means of the NLTE code CMFGEN. We explored their wind strengths and terminal velocities to address the Z dependence, over a large luminosity range. The empirical wind–luminosity relation (WLR) obtained updates and extends previous results in the literature. It reveals a luminosity and Z dependence, in agreement with the radiatively driven wind theory. For bright objects ($\log L/\mathrm{L}_\odot \gtrsim 5.4$), we infer that $\dot{M} \sim Z^{0.5-0.8}$. However, this dependence seems to get weaker or vanish at lower luminosities. The analysis of the terminal velocities suggests a shallow Z^n dependence, with $n \sim 0.1$–0.2, but it should be confirmed with a larger sample and more accurate v_∞ determinations. Recent results on SMC stars based on the PoWR code support our inferred WLR. On the other hand, recent bow-shocks measurements stand mostly above our derived WLR. Theoretical calculations of the WLR are not precise, specially at low L, where the results scatter. Deviations between our results and recent predictions are identified to be due to the weak wind problem and the extreme terminal velocities predicted by the models. The Z dependence suggested by our analysis deserves further investigations, given its astrophysical implications.

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Three new high-mass X-ray binaries in the Large Magellanic Cloud

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The Magellanic Clouds host a large population of high-mass X-ray binary (HMXB) systems, but although the Large Magellanic Cloud (LMC) is an order of magnitude more massive than the Small Magellanic Cloud, significantly fewer HMXBs are known. We conducted a search for new HMXBs in XMM–*Newton* observations, which we performed to investigate supernova remnant candidates in the supergiant shells LMC 5 and LMC 7. The three observed fields are located in regions, which were little explored in X-rays before. We analysed the XMM–*Newton* data to look for sources with hard X-ray spectrum and counterparts with optical colours and brightness typical for HMXBs. We report the discovery of three new Be/X-ray binaries, two of them showing pulsations in their X-ray flux. With a luminosity of 6.5×10^{34} erg s^{-1}, XMMU J045315.1−693242 in LMC 7 was relatively X-ray faint. The long-term OGLE I-band light curve of the $V = 15.5$ mag counterpart suggests a 49.6 day or 24.8 day orbital period for the binary system. XMMU J045736.9−692727, also located in LMC 7 was brighter with a luminosity of 5.6×10^{35} erg s^{-1} and hard spectrum with a power-law photon index of 0.63. The X-ray flux revealed clear pulsations with a period of 317.7 s. We obtained optical high resolution spectra from the $V = 14.2$ mag counterpart using the SALT-HRS spectrograph. Hα and Hβ were observed in emission with complex line profiles and equivalent widths of −8.0 Å and −1.3 Å, respectively. The I-band light curve obtained from OGLE shows a series of four strong outbursts followed by a sudden drop in brightness by more than 1 mag within 73–165 days and a recovery to the level before the outbursts. RX J0524.2−6620, previously classified as X-ray binary candidate, is located at the eastern part of LMC 5. We report the discovery of 360.7 s pulsations. (abridged)

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Three-dimensional simulation of a core-collapse supernova for a binary star progenitor of SN 1987A

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We present results from a self-consistent, non-rotating core-collapse supernova simulation in three spatial dimensions using a binary evolution progenitor model of SN 1987A. This 18.3-$M_\odot$ progenitor model is evolved from a slow merger of 14- and 9-$M_\odot$ stars, and it satisfies most of the observational constraints such as red-to-blue evolution, lifetime, total mass, and position in the Hertzsprung–Russell diagram at collapse, and chemical anomalies. Our simulation is initiated from a spherically symmetric collapse and mapped to the three-dimensional coordinates at 10 ms after bounce to follow the non-spherical hydrodynamics evolution. We obtain the neutrino-driven shock revival for this progenitor at $\sim$ 350 ms after bounce, leading to the formation of a newly born neutron star with average gravitational mass $\sim$ 1.35 $M_\odot$ and spin period $\sim$ 0.1 s. We also discuss the detectability of gravitational wave and neutrino signals for a Galactic event with the same characteristics as SN 1987A. At our final simulation time ($\sim$ 660 ms post-bounce), the diagnostic explosion energy, though still growing, is smaller (0.14 foe) compared to the observed value (1.5 foe). The ^{56}Ni mass obtained from the simulation (0.01 $M_\odot$) is also smaller than the reported mass from SN 1987A (0.07 $M_\odot$). Long-term simulation including several missing physical ingredients in our three-dimensional models such as rotation, magnetic fields, or more elaborate neutrino opacities should be done to bridge the gap between the theoretical predictions and the observed values.

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Dependence of pulsation mode of Cepheids on metallicity

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The Cepheid variables in SMC, LMC, the Milky Way, M 33 and M 31 are used to examine the dependence of pulsation mode on metallicity which was previously found in red supergiants. The initial samples of Cepheids are collected from the Cepheid catalogs identified from the OGLE, PS1, DIRECT, WISE and ZTF surveys. The contaminants are removed with the help of the Gaia/EDR3 astrometric information for extra galaxies or by comparing the geometric distance and the distance from the P–L relation for the Milky Way. The division of fundamental and first-overtone mode is refined according to the gap between the two modes in the P–L diagram of the objects in each galaxy. The ratio of FU/(FU+1O) is found to be 0.59, 0.60, 0.69, 0.83 and 0.85 for SMC, LMC, the Milky Way, M 33 and M 31 respectively in order of metallicity, which confirms that the pulsation mode depends on metallicity in the way that the ratio of FU/(FU+1O) increases with metallicity. This dependence is not changed if the incompleteness of the samples is taken into account.

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MUSE spectroscopic observations of the young massive cluster NGC 1850

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Context: The double cluster NGC 1850 in the Large Magellanic Cloud is the nearest young massive cluster of the Local Group with a mass similar to those of Galactic globular clusters. Recent studies have revealed an extended morphology of its main-sequence turn-off (MSTO), which can be interpreted as a spread in either age or internal rotation. In spite of its proximity, an accurate spectroscopic determination of its chemical properties is still missing.
Aims: We aim to investigate the general chemistry and the kinematics of this stellar system to test whether possible signs of multiple populations are observable in this cluster.
Methods: We analysed the spectra obtained with MUSE in adaptive optics mode of 1167 stars in both components of this cluster (NGC 1850A and NGC 1850B). Thanks to this data set, we were able to measure accurate global metallicities, Ba abundances, and radial velocities for a sample of 38 red supergiants and a guess of the oxygen abundance in the brightest turn-off stars belonging to NGC 1850A.
Results: We find an average metallicity of $\langle[\mathrm{M/H}]\rangle = -0.31 \pm 0.01$, a mean Ba abundance of $\langle[\mathrm{Ba/Fe}]\rangle = +0.40 \pm 0.02$, and a systemic radial velocity of $v_{\mathrm{LOS}} = 251.1 \pm 0.3$ km s^{-1}. The dispersion of the radial velocities suggests a dynamical mass of $\log(M/\mathrm{M}_{\odot}) = 4.84 \pm 0.1$, while no significant systemic rotation is detected. We detect a significant bimodality in O I line strength among the turn-off stars of NGC 1850A with $\sim 66\%$ of stars with $[\mathrm{O/Fe}] \sim -0.16$ and the rest with no detectable line. The majority of O-weak stars preferentially populate the red side of the MSTO and show H lines in emission, suggesting that they are Be stars rotating close to their critical velocity. Among normal MSTO stars, red stars have broader line profiles than blue ones, on average, suggesting a correlation between colour and rotational velocity.
Conclusions: The mean metallicity of this cluster lies at the metal-rich side of the metallicity distribution of the Large Magellanic Cloud following its age–metallicity relation. The Ba and O abundances agree with those measured in the bar of this galaxy. The correlation between line broadening and colour suggests that the observed colour spread among turn-off stars can be due to a wide range in rotational velocity covered by these stars.

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Disk precession to explain the super-orbital modulation of LMC X-4: results from the Swift monitoring campaign

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We studied the spectral changes of the high-mass X-ray binary system LMC X-4 to understand the origin and mechanisms beyond its super-orbital modulation (30.4 days). To this aim, we obtained a monitoring campaign with Swift/XRT (0.3–10 keV) and complemented these data with the years-long Swift/BAT survey data (15–60 keV). We found a self-consistent, physically motivated, description of the broadband X-ray spectrum using a Swift/XRT and a NuSTAR observation at the epoch of maximum flux. We decomposed the spectrum into the sum of a bulk+thermal Comptonization, a disk-reflection component and a soft contribution from a standard Shakura–Sunyaev accretion disk. We applied this model to 20 phase-selected Swift spectra along the super-orbital period. We found a phase-dependent flux ratio of the different components, whereas the absorption column does not significantly vary. The disk emission is decoupled with respect to the hard flux. We interpret this as a geometrical effect in which the inner parts of the

disk are tilted with respect to the obscuring outer regions.

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Blue Stragglers as tracers of the dynamical state of two clusters in the Small Magellanic Cloud: NGC 339 and NGC 419

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The level of central segregation of Blue Straggler stars proved to be an excellent tracer of the dynamical evolution of old star clusters (the so-called "dynamical clock"), both in the Milky Way and in the Large Magellanic Cloud. The A^+ parameter, used to measure the Blue Stragglers degree of segregation, has in fact been found to strongly correlate with the parent cluster central relaxation time. Here we studied the Blue-Straggler population of two young stellar systems in the Small Magellanic Cloud, namely NGC 339 (which is 6 Gyr old) and NGC 419 (with an age of only 1.5 Gyr), in order to study their dynamical state. Thanks to multi-epoch, high angular resolution *Hubble* Space Telescope observations available for both clusters, we took advantage of the stellar proper motions measured in the regions of the two systems and we selected a population of likely cluster members, removing the strong contamination from Small Magellanic Cloud stars. This enabled us to study, with unprecedented accuracy, the radial distribution of Blue Stragglers in these two extragalactic clusters and to measure their dynamical age. As expected for such young clusters, we found that both systems are poorly evolved from the dynamical point of view, also fully confirming that the A^+ parameter is a sensitive "clock hand" even in the dynamically-young regime.

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Spectroscopic evolution of very massive stars at $Z = 1/2.5$ $Z_\odot$

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Stars with masses in excess of 100 $M_\odot$ are observed in the Local Universe, but they remain rare objects. Because of the shape of the mass function, they are expected to be present only in the most massive and youngest clusters. They may thus be formed in number in highly star-forming galaxies. Very massive stars (VMSs) experience strong stellar winds that are stronger than those of their less massive OB-type counterparts. These strong winds therefore need to be taken into account in evolutionary models and synthetic spectra to properly predict the appearance of VMS. We present evolutionary models computed with the code STAREVOL. They include a recent mass-loss recipe that is relevant for VMSs. We subsequently calculated atmosphere models and synthetic spectra along the resulting tracks with the code CMFGEN. We studied stars with masses between 150 and 400 $M_\odot$ and focused on a metallicity $Z = 1/2.5$ $Z_\odot$. We studied the impact of our VMS spectra on the spectral energy distribution of young starbursts. We show that the optical and UV range is dominated by He II 4686 and He II 1640 emission for almost the entire main-sequence evolution of VMSs, in contrast to less massive stars. In the UV spectral range, carbon, nitrogen, and iron lines shape

the spectra of VMSs, which appear for most of their evolution as WNh objects. The morphology of the synthetic spectra is similar to that of VMSs in the Large Magellanic Cloud. We show that stars with masses higher than 100 $M_\odot$ emit nearly as much light as all other stars in young starbursts. The integrated UV spectrum of these starbursts is significantly affected by the presence of VMSs.

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The R 136 star cluster dissected with *Hubble* Space Telescope/STIS – III. The most massive stars and their clumped winds

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Context: The star cluster R 136 inside the Large Magellanic Cloud hosts a rich population of massive stars, including the most massive stars known. The strong stellar winds of these very luminous stars impact their evolution and the surrounding environment. We currently lack detailed knowledge of the wind structure that is needed to quantify this impact.
Aims: Our goal is to observationally constrain the stellar and wind properties of the massive stars in R 136, in particular the wind-structure parameters related to wind clumping.
Methods: We simultaneously analyse optical and ultraviolet spectroscopy of 53 O-type and three WNh-stars using the FASTWIND model atmosphere code and a genetic algorithm. The models account for optically thick clumps and effects related to porosity and velocity-porosity, as well as a non-void interclump medium.
Results: We obtain stellar parameters, surface abundances, mass-loss rates, terminal velocities, and clumping characteristics and compare them to theoretical predictions and evolutionary models. The clumping properties include the density of the interclump medium and the velocity-porosity of the wind. For the first time, these characteristics are systematically measured for a wide range of effective temperatures and luminosities.
Conclusions: We confirm a cluster age of 1.0–2.5 Myr and derived an initial stellar mass of $M \geq 250$ $M_\odot$ for the most massive star in our sample, R 136a1. The winds of our sample stars are highly clumped, with an average clumping factor of $f_{\rm cl} = 29 \pm 15$. We find tentative trends in the wind-structure parameters as a function of the mass-loss rate, suggesting that the winds of stars with higher mass-loss rates are less clumped. We compare several theoretical predictions to the observed mass-loss rates and terminal velocities and find that none satisfactorily reproduce both quantities. The prescription of Krtička & Kubát (2018) matches the observed mass-loss rates best.

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The VMC survey – XLVII. Turbulence-controlled hierarchical star formation in the Large Magellanic Cloud

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We perform a statistical clustering analysis of upper main-sequence stars in the Large Magellanic Cloud (LMC) using data from the Visible and Infrared Survey Telescope for Astronomy survey of the Magellanic Clouds. We map over 2500 young stellar structures at 15 significance levels across ~ 120 square degrees centred on the LMC. The structures have sizes ranging from a few parsecs to over 1 kpc. We find that the young structures follow power-law size and mass distributions. From the perimeter-area relation, we derive a perimeter-area dimension of 1.44 ± 0.20. From the mass–size relation and the size distribution, we derive two-dimensional fractal dimensions of 1.50 ± 0.10 and 1.61 ± 0.20, respectively. We find that the surface density distribution is well-represented by a lognormal distribution. We apply the Larson relation to estimate the velocity dispersions and crossing times of these structures. Our results indicate that the fractal nature of the young stellar structures has been inherited from the gas clouds from which they form and that this architecture is generated by supersonic turbulence. Our results also suggest that star formation in the LMC is scale-free from 10 pc to 700 pc.

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The hydrogen clock to infer the upper stellar mass

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The most massive stars dominate the chemical enrichment, mechanical and radiative feedback, and energy budget of their host environments. Yet how massive stars initially form and how they evolve throughout their lives is ambiguous. The mass loss of the most massive stars remains a key unknown in stellar physics, with consequences for stellar feedback and populations. In this work, we compare grids of very massive star (VMS) models with masses ranging from 80–1000 $M_\odot$, for a range of input physics. We include enhanced winds close to the Eddington limit as a comparison to standard O-star winds, with consequences for present-day observations of $\sim$ 50–100-$M_\odot$ stars. We probe the relevant surface H abundances (X_s) to determine the key traits of VMS evolution compared to O stars. We find fundamental differences in the behaviour of our models with the enhanced-wind prescription, with a convergence on the stellar mass at 1.6 Myr, regardless of the initial mass. It turns out that X_s is an important tool in deciphering the initial mass due to the chemically homogeneous nature of VMS above a mass threshold. We use X_s to break the degeneracy of the initial masses of both components of a detached binary, and a sample of WNh stars in the Tarantula nebula. We find that for some objects, the initial masses are unrestricted and, as such, even initial masses of the order 1000 $M_\odot$ are not excluded. Coupled with the mass turnover at 1.6 Myr, X_s can be used as a 'clock' to determine the upper stellar mass.

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KMHK 1762: Another star cluster in the Large Magellanic Cloud age gap

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Context: The star cluster (SC) age distribution of the Large Magellanic Cloud (LMC) exhibits a gap from ~ 4 to 10 Gyr ago, with an almost total absence of SCs. Within this age gap, only two confirmed SCs have been identified hitherto. Nonetheless, the star field counterpart does not show the same characteristics, making the LMC a peculiar galaxy where the star formation history and cluster formation history appear to differ significantly.
Aims: We re-analysed the colour–magnitude diagram (CMD) of the KMHK 1762 SC by using the deep optical photometry provided by the "Yes, Magellanic Clouds Again" survey, so as to robustly assess its age.
Methods: First, we partially removed foreground and/or field stars by means of parallaxes and proper motions obtained from the Gaia Early Data Release 3. Then, we applied the Automated Stellar Cluster Analysis package to the cleaned photometric catalogue to identify the isochrone that best matches the CMD of KMHK 1762.
Results: The estimated age of KMHK 1762 is $\log t = 9.74 \pm 0.15$ dex (~ 5.5 Gyr), which is more than 2 Gyr older than the previous estimation which was obtained with shallower photometry. This value makes KMHK 1762 the third confirmed age-gap SC of the LMC.
Conclusions: The physical existence of a quiescent period of the LMC SC formation is questioned. We suggest it can be the result of an observational bias, originating from the combination of shallow photometry and limited investigation of the LMC periphery.

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