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Stellar Clusters in 4MOST

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The 4MOST Stellar Clusters Survey will target essentially all the Galactic globular and open clusters and star-forming regions accessible to 4MOST (about 120 globulars, 1800 open clusters and 80 star-forming regions). This will: shed light on how clusters form, evolve, dissolve, and populate the Milky Way; calibrate complex physics that affects stellar evolution, on which our ability to measure accurate ages ultimately rests; and evaluate the contribution of star clusters to the formation and evolution of the individual Galactic components with unparalleled statistics.

Scientific context

Traditionally, in the Milky Way (MW) stellar clusters are classified as open clusters (OCs) — low-mass (tens to thousands of stars) objects spanning the whole age range of the disc — and globular clusters (GCs, tens to hundreds of thousands of stars), which are massive, old, and associated with all major Galactic components. Younger GCs are present in the Local Group; for example, the Magellanic Clouds (MCs) host a population of GCs spanning all age ranges.

Clusters are expected to play an important role in the buildup of the Galactic components (see, for example, the cosmological E-MOSAIC simulations; Pfeffer et al., 2018 — and the association of clusters with the different merger events; for example, Massari, Koppelman & Helmi, 2019). The study of the formation, evolution and properties of clusters and their stellar populations is a fundamental ingredient to further our understanding of key issues related to the formation and evolution of the MW and galaxies in general. These issues are set out below.

Cluster formation and disruption. Stars are thought to form in associations and clusters, the vast majority of which disperse because of dynamical and stellar evolutionary effects, such as supernova feedback. Studying clusters is therefore a key ingredient in the understanding of both star formation and how they populate the Galactic components through disruptive processes. It is currently still unclear whether OCs are the dominant source of stars in the disc, what the role of GCs in building up the Galactic bulge and halo is, and how the multiple populations, a phenomenon observed in virtually all Galactic GCs, form. Chemical information and radial velocities (RVs) for a large sample of clusters, along with Gaia astrometry and precise and independent ages from asteroseismology, will be necessary to make headways on these matters.

Stellar evolution. Our understanding of stellar populations ultimately relies on stellar models: stellar age dating is necessary to investigate galactic formation and evolution and processes such as mass loss and feedback are crucial ingredients in probing the chemical evolution of galaxies. However, the physics of many processes (accretion, convection, rotation, magnetic field, atomic diffusion, mixing, activity, stellar winds, mass loss) is uncertain and is treated in different, simplified ways in stellar models. The large, homogeneously selected and analysed samples of clusters at different ages and chemical compositions we will collect will contribute to considerable advancements in detailed stellar modeling, providing empirical isochrones and calibration of the associated physics.

MW formation. Clusters can be accurately dated and hence their study allows us to place further constraints on Galactic formation, evolution, and structure, complementing the study of the field population. The study of the chemo-dynamical properties of stellar clusters provides important information on the merger events involved in the assembly history of our galaxy. The age-metallicity relation of the MW disc, its radial, azimuthal and vertical metallicity distributions, and their evolution with time can be studied through OCs. The chemo-dynamic study of GCs can answer several major open questions about the Galactic halo and bulge, such as how they came into place, and can help probe the evolution of the MCs and the role of interactions with the MW.

Specific scientific goals

The 4MOST Stellar Clusters Survey aims to obtain spectra of the largest[a] uniformly selected and analysed sample of Galactic clusters (and a few MC GCs) and very young clusters (VYCs) in star-forming regions (SFRs), covering metallicities from the [Fe/H] = –2.5 dex of GCs to super-solar OCs and ages from a few Myr to 13.5 Gyr. We will derive chemical characterisation, probe cluster internal kinematics up to the outskirts, examine dissolving (and dissolved) clusters, and probe the presence and nature of halos and tidal tails. Considering the expected performance of 4MOST, in the time allocated to our survey we expect to reach the following goals:

- Derive homogeneous, full chemo-dynamical characterisation (at 0.05 to 0.1 dex precision) for an unprecedented sample of ~ 120 GCs in the MW and MCs, including a few newly identified bulge GCs. Elemental abundances probing all nucleosynthetic channels (Fe-peak, light, α, p- and n-capture) will be obtained from high-resolution (HR) spectra for a few tens of stars per cluster (the actual number depending on distance, reddening and concentration) for ~ 5 000 stars with $G < 16.5$. As concerns the study of multiple populations, we will obtain precise abundances of O, Na, Mg and Al, i.e., of the elements defining the classical (anti-)correlations between light elements; this cannot be done using photometry, which traces essentially just N variations (Gratton et al., 2019). RVs, atmospheric parameters, and a few key elements (for example α's) will be determined from low-resolution (LR) spectra for ~ 35 000 stars with $16.5 < G < 20$ (several tens per cluster) in 140 GCs. This will be by far the largest sample of homogeneously derived detailed compositions and RVs for GC stars.
- Derive chemical abundances (at 0.05 to 0.1 dex precision) in all the nucleosynthetic channels for the vast majority of known OCs accessible to 4MOST. We expect to study ~ 30 000 stars at HR ($G < 14.5$ for most clusters, with $G < 15.5$ in a few tens of clusters, selected to study details of the composition down to the main sequence) and ~ 75 000 at LR ($14.5 < G < 19$). Again, this will be by far the largest sample of homogeneously derived chemical abundances and RVs for OCs.
- Derive the dynamics, study activity indicators and probe the composition of ~ 80 VYCs in nearby SFRs, where stars are still in the pre-main-sequence phase (PMS), and study low-mass PMS stars from already dissolved VYCs.

Subsurvey	Targets	Resolution	*G* Magnitude range	N expected successfully observed targets
GC HR	MW and MCs GCs	HRS	10–16.5	~ 5000
GC LR	MW and MCs GCs	LRS	16.5–20	~ 35 000
OC HR	MW OCs	HRS	10–14.5 10–15.5 (in selected OCs)	~ 30 000
OC LR	MW OCs	LRS	14.5–19 15.5–19 (in selected OCs)	~ 75 000
VYC HR	MW VYCs	HRS	10–15	~ 4000
VYC LR	MW VYCs	LRS	15–18	~ 10 000

Table 1. Magnitude ranges and expected successful target numbers for the six sub-surveys.

This unprecedented suite of homogeneous and precise elemental abundances and RVs, in combination with the datasets and results obtained by the 4MOST Galactic Consortium Surveys, Gaia data, stellar and dynamical models, will allow us to:

- determine key properties (such as composition, kinematics and, in GCs, the incidence of the multiple population phenomenon) across a wide range of cluster properties;
- characterise cluster velocity fields in three dimensions, investigate their dispersions and rotation as a function of radius, probing the outskirts of a large sample of clusters for the first time; quantify processes such as evaporation, tidal stripping, dynamical ejection, and possibly GC black hole retention;
- build a homogeneous database to be compared with the predictions of stellar evolutionary models. This, together with asteroseismology, will impact on a number of fundamental issues, such as the initial mass function slope and its universality, the timescale of star formation and star formation histories, improving field-star age determination. The calibration of the stellar models, when coupled with multi-band photometry, will also provide stellar fiducials (for the different sub-populations, in the case of GCs) for population synthesis models that will be used to interpret the properties of unresolved stellar populations in distant galaxies;
- derive constraints on PMS models, which currently have factors of two uncertainties in predictions of mass and age, thanks to key information (rotational velocity, atmospheric parameters, RVs, activity indicators) for representative samples of PMS stars (either still inside their native VYC or already lost). This will help establish the empirical timescales for star and planet formation, disc dispersion and the dynamical timescales for cluster dissolution;
- investigate the early evolution of clusters and their interplay with their environment; identify the stars lost from clusters (or belonging to dissolving/dissolved clusters) through chemo-dynamical tagging, thus constraining their role in the buildup of the Galactic components;

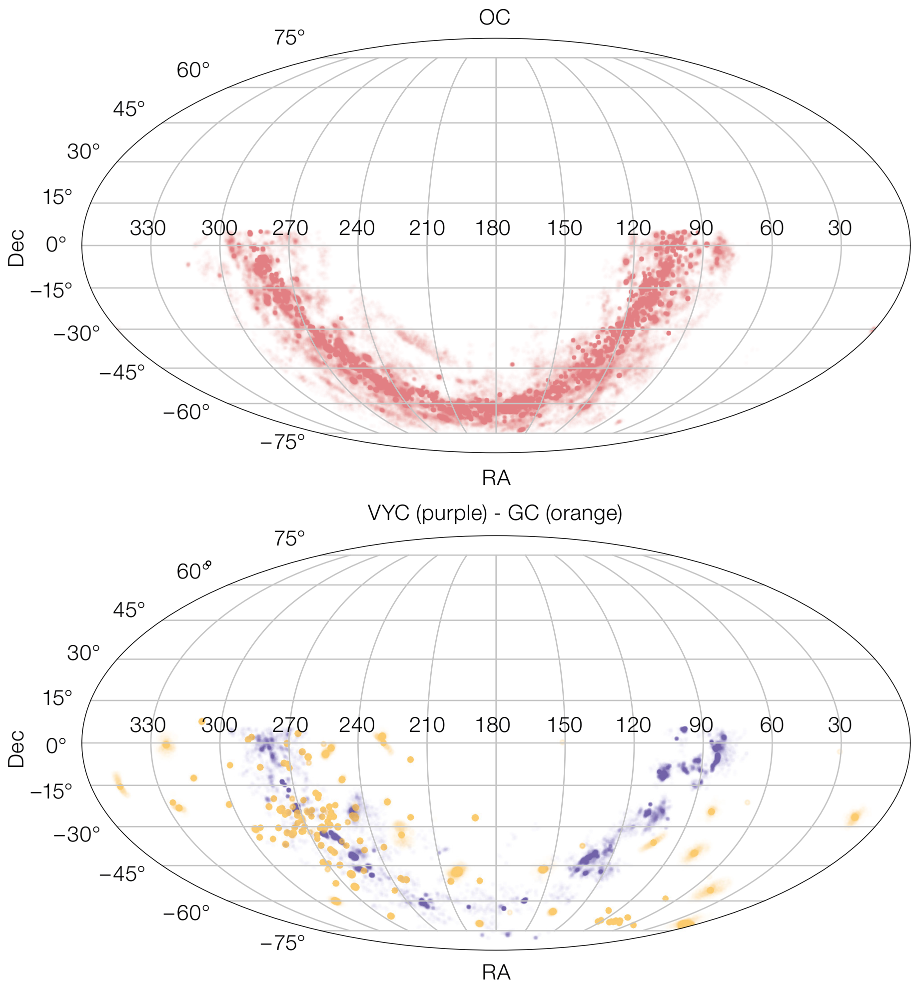

Figure 1. Spatial distribution of the targets in the input catalogue for our survey. OCs are shown in the upper panel, while GCs and VYCs are shown in the lower panel, in orange and purple respectively.

- precisely and homogeneously trace the chemical abundance distributions and gradients in the disc, along with their evolution, including the so far poorly quantified effect of radial mixing, which spreads chemical signatures associated with a star/cluster birthplace across a range of Galactocentric distances;
- define a uniform metallicity scale from [Fe/H] = −2.5 to +0.5 dex, for dwarfs and giants, for stars of a large range of age (i.e., mass), providing an ideal sample for both internal calibration of the Galactic 4MOST surveys and for cross-calibration with other large surveys.

Target selection

Each class of objects — GCs, OCs, and VYCs — has two dedicated sub-surveys, one in HR and one in LR, making a total of six sub-surveys.

Most of our targets are located in fields with considerable contamination (for example OCs and VYCs in the disc, GCs in the bulge and the MCs) and are characterised by high spatial densities (especially GCs). Careful attribution of membership is crucial, as it is to exclude stars with bright neighbours which can act as contaminants in the collected spectra.

The grand total of selected targets for the input catalog in HR is ~ 100 000, while in LR it is close to 300 000, a number considerably larger than the number of stars we aim to observe. This strategy has been adopted to allow flexibility for the tiling and allocation algorithms, which operate on the combined catalogue for all the 4MOST surveys, while ensuring the maximisation of the number of successfully observed targets. Estimates of the number of stars we will successfully observe, based on simulations performed within the 4MOST collaboration, are listed in Table 1, along with a few key facts about targets for the six sub-surveys. More details of the criteria for the different classes of objects in our sample are given below along with a visual representation of the input catalogue target distribution in Figure 1.

GCs. Our aim is to target all visible GCs, from centre to outskirts (comprising halos and tails). Targets are selected on Gaia DR3 astrometry (for example, Vasiliev & Baumgardt, 2021) and colour–magnitude diagrams. To allow for an easier allocation, LR targets were selected to be outside a few core radii from the centre of the clusters, where the bulk of HR stars are located. Magnitude ranges for LR and HR targets are reported in Table 1. All selected targets are of FGK spectral type; (almost) all HR targets are giants, while both giants and dwarfs are observed in LR mode.

OCs. We plan to observe all OCs accessible to 4MOST, sampling from the centre to the outskirts. The original selection based on Gaia DR2 membership (based, for example, on Cantat-Gaudin et al., 2020) was refined with Gaia DR3. Targets were selected to be of spectral type FGK (both giants and dwarfs), with $A_V < 2$. HR targets were selected to have $10 < G < 14.5$, with the exception of a few tens of OCs, chosen to study the detailed chemistry down to the main sequence, where we selected targets with $10 < G < 15.5$. LR targets span from the faint end of the HR to $G = 19$. Stars bright enough for HR, but with Gaia DR3 broadening parameter $v_{broad} > 30$ km s^{-1}, have been included in the LR rather than HR sample, as for objects of such rotational velocity HR does not allow to derive additional information over LR. The HR sample includes red-clump stars out to distances of ~ 10 kpc, and the LR sample includes faint K stars within 6 kpc.

VYCs. We selected targets from the catalogues of Dias et al. (2002, and revised online in 2015[1]) and Cantat-Gaudin et al. (2020), including all VYCs in the 4MOST footprint for which a signal-to-noise ratio of about 40 $\AA^{-1}$ could be reached in 1 hour of exposure time in HR. This includes objects within 2.5 kpc of the Sun, with reddening $E(B-V) < 2.5$, and ages 2–20 Myr. Magnitude ranges for LR and HR targets are reported in Table 1. Stars brighter than $G = 15$, but with Gaia DR3 broadening parameter $v_{broad} > 30$ km s^{-1}, have been included in the LR rather than the HR sample.

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Links

[1] Revised catalogue of optically visible open clusters (after Dias et al., 2002): http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/389/871

Notes

[a] Actually, the Gaia RVS instrument is producing the largest database of intermediate resolution spectra, providing RVs, metallicity and a set of chemical abundances for ten of millions stars; some of those belong to stellar clusters (see Gaia Collaboration et al., 2023, where the metallicity of about 600 open clusters has been derived from an average of three member stars). However, the magnitude limit for Gaia spectroscopy is bright (implying that GC stars are rarely observed), only a limited set of abundances is measured, and there is no controlled selection of cluster stars to be observed.

This infrared image shows the star-forming region 30 Doradus, also known as the Tarantula Nebula, highlighting its bright stars and light, pinkish clouds of hot gas. The image is a composite: it was captured by the HAWK-I instrument on ESO's Very Large Telescope (VLT) and the Visible and Infrared Survey Telescope for Astronomy (VISTA).