LETTER TO THE EDITOR

The star formation history of a Galactic halo building block: The Helmi streams

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ABSTRACT

Aims. We aim to determine the star formation history (SFH) of the progenitor of the Helmi streams.

Methods. From the 5D Gaia EDR3 data set, we extract local samples of stars dominated by the Helmi streams, and the Galactic (thick and thin) disc and halo. We do this by identifying regions in a pseudo-Cartesian velocity space (obtained by setting line-of-sight velocities to zero), where stars belonging to these components, as identified in samples with 6D phase-space information, are predominantly found. We make use of an updated absolute colour-magnitude diagram (aCMD) fitting methodology to contrast, for the first time, the SFH of a disrupted accreted system -the Helmi streams- to that of the average Milky Way inner halo. To this end, special attention is given to the correct characterisation of Gaia completeness effects and observational errors on the aCMD.

Results. We find that the progenitor of the Helmi streams experienced an early star formation but which was sustained for longer (until 7–9 Gyr ago) than for the Milky Way halo (10–11 Gyr ago). As a consequence, half of its stellar mass was in place ~ 0.7 Gyr later. The quenching of star formation in the Helmi streams progenitor, together with some hints of a star formation burst at ~ 8 Gyr, suggest it was accreted by the Milky Way around this time, in concert with previous estimates based on the dynamics of the streams.

Key words. Galaxy: halo – Galaxy: kinematics and dynamics – Galaxy: stellar content

1. Introduction

Galaxies are the outcome of the complex interplay between internal, secular processes and the accretion of external stellar systems and intergalactic gas (e.g. Kormendy & Kennicutt 2004; Sancisi et al. 2008; Hirschmann et al. 2012). Galaxy accretion in particular, is a very defining process. Mergers can both drive morphological and dynamical changes in the host galaxy, as well as trigger the formation of new stars (e.g. Barnes 1988; Pearson 2009), making them crucial for unraveling the ancient history of galaxies including our own, the Milky Way (MW). In fact, the thorough characterisation of the stellar content of the MW halo has allowed unveiling many of our Galaxy’s building blocks (e.g. Ibata et al. 1994; Helmi et al. 1999, 2018; Belokurov et al. 2018; Myeong et al. 2018; Koppelman et al. 2019a; Naidu et al. 2020). Thanks to current and ongoing, ground and space-based large surveys (e.g. Gaia Collaboration 2021; Liu et al. 2019; Ahumada et al. 2020; Steinmetz et al. 2020b; Buder et al. 2021) we are now in a position to characterise the systems from which our own Galaxy grew (Gallart et al. 2019; Vincenzo et al. 2019; Aguado et al. 2021a; Matsuno et al. 2021).

The identification of stars linked to each of the MW building blocks is commonly done based on the dynamical properties of halo stars such as integrals of motion or action space (Helmi & de Zeeuw 2000; Myeong et al. 2018; Lövdal et al. 2022). In some cases chemical information is added (Naidu et al. 2020; Ruiz-Lara et al. 2022). This approach requires the precise determination in three dimensions of both stellar positions and velocities. Unfortunately, although large samples of stars with known 6D phase-space information have become available with the advent of Gaia data (Gaia Collaboration et al. 2021), the number of halo stars in these samples is still very limited. This, together with completeness and selection effects (Everall & Boubert 2022) especially affecting faint magnitudes, limits considerably the characterisation of the hitherto known building blocks of our Galaxy.

In this work, we exploit an alternative approach to isolate samples of stars possibly associated to the Helmi streams (Helmi et al. 1999), in an attempt to reconstruct the star formation history (SFH) of their progenitor. To this end, we use 5D information, namely their position on the sky, distance and proper motions. The Helmi streams are debris from a galaxy (~ 10⁶ M☉ in stars) accreted between 5 and 8 Gyr ago (e.g. Kepley et al. 2007; Koppelman et al. 2019b). Recent work has reported chemical patterns in the streams’ stars that distinguish them from other halo stars (Aguado et al. 2021b; Nissen et al. 2021; Matsuno et al. 2022) suggesting different formation histories. We find compelling evidence that indeed the progenitor dwarf galaxy continued forming stars for longer than the average halo near the Sun, until it stopped approximately 7 to 9 Gyrs ago, possibly due to its accretion onto the MW.
2. Data and sample selection

We consider stars from Gaia EDR3 (Gaia Collaboration et al. 2021) with parallax_{over_error} > 5, and good phot_bp_rp_excess_factor (see Ruiz-Lara et al. 2022), and which are located within 2.5 kpc from the Sun, as determined by inverting their parallax after applying a global zero-point offset (Lindegren et al. 2021). For all stars in this local sample, we compute their absolute colour (G_BP - G_RP) and G-magnitude (M_G) using their parallax, and correct for extinction (E(Bp-Rp) and A_G), from Green (2018); Green et al. (2019), with the recipes presented in Gaia Collaboration et al. (2018).

To guide our selection of Helmi stream stars in 5D, we first identify a sample of halo stars with 6D information. This is obtained for the above local sample by complementing the radial velocities from Gaia EDR3 with V_{LSR} measurements from GALAH DR3 (Buder et al. 2021), APOGEE DR16 (Ahumada et al. 2020), RAVE DR6 (Steinmetz et al. 2020b,a), and LAMOST DR6 (Liu et al. 2019; Wang et al. 2020). Velocity systematic shifts between surveys, although small (see Tsantaki et al. 2022), have been considered. We select halo stars by requiring that |V - V_{LSR}| > 210 km/s, where V is the total velocity vector corrected for the Solar motion and Local Standard of Rest velocity (V_{LSR} = 232 km/s from McMillan 2017).

The 5D halo sample is extracted from the local sample as follows. For stars near the Galactic plane (|b| < 20°), we consider candidate halo stars those with a tangential velocity v_t = 4.74/parallax_{G} x (μ_a^G + μ_D^G)^{1/2} > 230 km/s. For stars with |b| > 20°, we assign the v_{los} in the 6D Gaia (local) sample that is closest in the space of (α, δ, parallax), thus obtaining a fictitious V_{los}. Then, we apply the same criterion as in 6D, namely |V - V_{LSR}| > 210 km/s. In both cases, we keep only stars with M_G < 5.

Using the criteria from Koppelman et al. (2019b), Dodd et al. (2022), and Lövdal et al. (2022), we identify 646 candidate members of the Helmi streams in the 6D halo sample. Ideally, one would compute the SFH of the progenitor of the Helmi streams from this subset. Unfortunately, the limited number of stars available and the complex selection functions (from Gaia as well as the various spectroscopic surveys used) hinder this approach. This is why, we turn to the 5D halo sample and select tentative Helmi member stars using their pseudo-Cartesian velocities. These are obtained by computing the velocities in Cartesian coordinates assuming v_{los} = 0 (see Eq. 6 of Koppelman & Helmi 2021, for the exact expressions). Figure 1 displays the distribution of the Helmi streams stars from the 6D subsets in this pseudo-Cartesian velocity space (green points). Although the distinctive clustering in v_α vs. v_δ that led to the discovery of the Helmi streams is less prominent in this pseudo space, some differentiation is still possible as there are clear regions in v_γ vs. v_δ, where the streams stars are more dominant.

We thus proceed to define three different subsamples from the 5D halo by considering the stars contained within the green contours in Fig. 1. We name these selections HelmiA (~48000), HelmiB (~23000), and HelmiC (~7000 stars), where we have kept only stars with A_G < 0.5 as these will be used for the computation of SFHs (Ruiz-Lara et al. 2020). The HelmiC is the strictest subset, and thus, in principle has the least amount of contamination. In addition, we select a sample representative of the halo by considering stars with negative v_γ (“retrograde halo”, black rectangle, ~96000 stars). We also define a (thin + thick) disc-dominated sample (cyan, dashed polygon, ~12000 stars), where disc stars seem to dominate in pseudo-Cartesian velocity space as inferred from comparison to a 6D sample (defined by stars with |V - V_{LSR}| < 210 km/s, blue contours and points). In the next section, we compute the SFHs characteristic of these various sets. Given the selection process there is likely contamination in all of the Helmi streams subsets, but we also expect that intrinsic differences in the formation histories of the MW halo and the progenitor of the Helmi streams should reveal themselves through our analysis.

3. Methodology

Fitting an absolute colour-magnitude diagram (aCMD) has proven to be an efficient way of retrieving SFHs of stellar systems, including our own Galaxy (e.g. Gallart et al. 1999, 2019; Tolstoy et al. 2009; Cignoni & Tosi 2010; Ruiz-Lara et al. 2020). In this work we use an updated aCMD fitting methodology tailored for Gaia data. All the details are reported in Gallart et al. (in prep.). Here, we provide a brief description.

3.1. Synthetic aCMD: Completeness and error simulation

We will compare the various 5D samples selected in Sect. 2 with a synthetic aCMD that contains 40 million stars (with −3 < M_G < 5) with a flat distribution of age and metallicity (Z) ranging from 0.02 to 13.5 Gyr and 0.0001 to 0.032, respectively. We compute this synthetic aCMD using the updated BaSTI stellar evolutionary models (Hidalgo et al. 2018) in its α-enhanced version (Pietrinferni et al. 2021), with a Reimers mass loss parameter (η) of 0.3, assuming a Kroupa initial mass fraction (Kroupa 2001), a fraction of unresolved binaries (β) of 30%, and a minimum mass ratio for binaries (q) of 0.1.

The full Gaia 5D dataset has unprecedented photometric precision and is basically complete in the volume and absolute colour-magnitude range covered in this work. In particular, within a parallax (or distance cut) of 1/2.5 mas the set reaches a completeness > 99% for absolute magnitudes −3 < M_G < 5,
i.e. below the oldest main sequence turn-off (see Mor et al. 2019; Everall & Boubert 2022). However, the subsets identified in the previous section were subject to several quality cuts, and these may affect the distribution of stars in the aCMD potentially biasing our inference of SFHs.

To account for the associated selection effects, we construct parent subsamples aimed to be analogues to the HelmiA-C, retrograde halo, and disc-dominated 5D subsets identified in Sect. 2. These are extracted from the 5D Gaia sample in the 2.5 kpc volume using the same approach (see Fig. 1) as before but without imposing any quality cuts. As in Sect. 2, we compute a tangential velocity $v_t$ and a fictitious $V'$ by inverting the parallax to infer a distance. Note that computing a distance without an error cut could lead to incorrect distances, but this is exactly one of the effects we want to simulate.

We simulate the effect of the quality cuts as well as photometric errors as follows. To each synthetic star we assign $(l-b$-parallax) based on the global distribution of the corresponding parent sub-sample (be it the counterpart of the HelmiA-C, retrograde or disc-dominated haloes). This allows us to shift the synthetic aCMD to an apparent CMD and compute extinction for each star (Green et al. 2019). In a second step, we assign values of the phot_bp_rp_excess_factor, parallax_over_error, and photometric errors (in the three Gaia bands) to each synthetic star from an observed star with a similar absolute colour and magnitude (within 0.02 magnitudes). Sometimes such a counterpart does not exist (for example if the observed population is predominantly old, there will not be young bright main sequence stars which are however, generated in the synthetic aCMD). In this case, we simulate these properties by fitting how the quality parameters vary as a function of colour and apparent magnitudes for the parent sub-sample. Finally, new, error-convolved absolute colours and magnitudes are computed for each synthetic star considering the attributed photometric and parallax errors and extinction values (Green et al. 2019). This allows us to mimic the effect of observational errors blurring features in the aCMD.

After simulating the effect of errors, we consider the issue of completeness in two separate steps. First, although nearly negligible for the volume and the colour-magnitude ranges considered here, we use the Gaia selection function (Everall & Boubert 2022) to evaluate whether a given synthetic star (based on its assigned $l$, $b$, and simulated apparent $G$-magnitude) would be included in the 5D Gaia EDR3 catalogue. Secondly, we apply the same quality cuts described in Sect. 2 (on parallax_over_error, phot_bp_rp_excess_factor, and $A_g$). The outcome of this procedure is an error-convolved synthetic aCMD that is affected by Gaia observational and selection effects in a similar way as our observed sub-samples.

3.2. Computing star formation histories
The derivation of the SFHs for our various sub-samples is done using dirSFH (Gallart et al. in prep.), which is an improvement and extension of the well-known tools IACpop (Aparicio & Hidalgo 2009) and TheStorm (Bernard et al. 2018). In short, dirSFH defines a series of simple stellar populations (SSPs) from the error-convolved synthetic aCMD using a dirichlet tesselation (Green & Sibson 1978) from a grid of seed points within the available range of ages and metallicities. The code then finds the combination of SSPs that best fits the observed aCMD based on the Skellam probability distribution of the difference between two statistically independent distributions (observed and simulated aCMD). It includes two different weighting strategies as a function of colour and magnitude, namely “uniform”, or “weighted” (as the logarithm of the inverse of the variance of the ages across the synthetic aCMD). As this weighting scheme already gives which parts of the aCMD provide more information to the recovery of the SFH, a single region/bundle encompassing the whole aCMD is used (see Fig. 2), in contrast to e.g. Monelli et al. (2010). The final SFH is derived from the weighted average of 100 individual solutions that are obtained by slightly modifying each time the grid of seed points, and thus, the tessellation in age and metallicity. The uncertainties are directly derived from the variance of the combination. Extensive testing using different synthetic aCMDs (stellar models, unresolved binary recipes, etc.) and dirSFH internal parameters (age-metallicity grids, weighting strategies, etc.) reveal that the solutions are robust (see Appendix A).

Figure 2 shows the aCMD fitting approach applied to the HelmiC sub-sample. The residuals of the fit (right most panel) are small and homogeneous across the whole aCMD, indicative...
4. Results and discussion

Figure 3 shows the normalised star formation rate (SFR) as a function of age and [Fe/H] for the three different sub-samples HelmiA-C (top panels) and the disc-dominated and retrograde halo. Comparing the top panels for the Helmi streams (in decreasing order of contamination) we see two main trends: i) stars older than 8 Gyr with [Fe/H] ∈ (−1.0, −0.4) tend to be less dominant and almost absent in HelmiC; and ii) the metal-poor ([Fe/H] ∼ −1.5) population gradually extends to younger ages (from up to 11 Gyr in HelmiA to nearly 9 Gyr in HelmiC). Trend i) is a direct consequence of the HelmiB and HelmiC sub-samples presenting a lower amount of contamination from (thick) disc stars (see Fig. 1) as a comparison to the bottom-left panel reveals. Point ii) suggests that the Helmi streams progenitor experienced early star formation that extended to younger ages than the population contaminating these samples.

We also note an accumulation of ∼ 8 Gyr old stars with [Fe/H] ∼ −1 for HelmiC. Although clearly apparent in our preferred set-up to derive SFHs (described in Sect. 3), in tests varying the weighing schemes, binary fraction and other parameters, this feature appears ∼ 60% of the time, implying it should be interpreted with caution.

Focusing on the bottom panels of Figure 3 for the "retrograde halo" and the "disc(s)-dominated halo" we find that the halo sub-sample is dominated by old and metal-poor stars, in agreement with current knowledge (Helmi 2020). The extension that is seen to higher metallicities and young ages is possibly a consequence of disc(s) stars contamination, as a comparison of these bottom panels shows. This results are independent of the exact selection of the halo sample, all of which yield consistent SFHs.

5. Conclusions

In this letter we have determined the SFH of the progenitor of the Helmi streams using a sample of nearby tentative members extracted from the 5D Gaia EDR3 data set. We have found that the progenitor of the streams displayed a more extended star formation history than a comparison sample representative of the Milky Way halo, as well as an average lower metallicity. In addition, we clearly have detected the quenching of its star formation ∼ 7 to 9 Gyr ago, which may have coincided with its accre-
Fig. 4: Comparison of the SFHs of the Helmi streams (green) with that of a halo sample (black), both selected in 5D. Top: Normalised SFR as a function of age. Bottom: Cumulative metalliclicity distribution function (MDF). The SFHs in the upper panel have been normalized to their peak value.
Fig. A.1: Comparison of the SFHs of the 5D Helmi streams (green) with that of the halo stars selection (black) for different configurations of dirSFH. Left to right: i) effect of weighting scheme, in all cases we use the weighted option except in this first panel where we assess the effect of an uniform weighting (dashed lines); ii) different version of BaSTI models (Pietrinferni et al. 2004); iii) and iv) different recipes for modelling unresolved binaries in the synthetic aCMD. In the three right-most panels we indicate the preferred solution discussed throughout the paper as dashed lines for comparison. All SFHs are normalised to their peak value.

Appendix A: Assessing the robustness of the method

Figure A.1 displays the comparison between the SFH of the HelmiC and Halo 5D samples as obtained using different configurations of dirSFH. The left hand panel highlights the little effect of the weighting scheme in our solutions (for the particular case of our preferred configuration).

In all tests we see how our main result, i.e. the Helmi stream progenitor displays a more extended early SFH with respect to the overall halo, holds (see Fig. A.1). It is only minimised (differences of 0.2 Gyr in the half-mass formation time), when an extreme amount of unresolved binaries is included in the synthetic aCMD ($\beta=70\%$). Whereas the recovery of the SFH of HelmiC is nearly unaffected in this case, the halo solution displays lower metallicities than what found from spectroscopic surveys, which is compensated in the dirSFH solution with younger ages (age-[Fe/H] degeneracy), and thus minimising differences between the SFH of the Helmi progenitor and the halo. Belokurov et al. (2020) studied the variation of the fraction of unresolved binaries in the aCMD using Gaia DR2 data, finding that, in the range of colours and magnitudes sampled in this work, the fraction of unresolved binaries is $\sim 30\%$ (same fraction assumed in this work). All this can be used as evidence supporting our choice, the robustness of the method, and confirms that the progenitor of the Helmi streams had a more extended period of early star formation than the MW halo.