The age structure of the Milky Way’s halo

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We present a new, high-resolution chronographic (age) map of the Milky Way’s halo, based on the inferred ages of ~130,000 field blue horizontal-branch (BHB) stars with photometry from the Sloan Digital Sky Survey. Our map exhibits a strong central concentration of BHB stars with ages greater than 12 Gyr, extending up to ~15 kpc from the Galactic Centre (reaching close to the solar vicinity), and a decrease in the mean ages of field stars with distance by 1–1.5 Gyr out to ~45–50 kpc, along with an apparent increase of the dispersion of stellar ages, and numerous known (and previously unknown) resolved over-densities and debris streams, including the Sagittarius Stream. These results agree with expectations from modern lambda cold dark matter cosmological simulations, and support the existence of a dual (inner/outer) halo system, punctuated by the presence of over-densities and debris streams that have not yet completely phase-space mixed.

The formation and evolution of the recognized stellar components of the Milky Way—its central bulge, disk and halo—are among the most fundamental and actively explored areas in contemporary astronomy. This is due, to a great extent, to the rapid expansion of photometric and spectroscopic information acquired by recent large-scale surveys such as the Sloan Digital Sky Survey¹ (SDSS), the Radial Velocity Experiment² (RAVE) and the Gaia-ESO Survey³ (GES), as well as previous dedicated searches for chemically primitive stars by the HK Survey⁴,⁵ and Hamburg/ESO Survey⁶. The moderate- to high-resolution spectroscopy from such surveys provides the basic data, such as stellar atmospheric parameters (effective temperature, surface gravity, and metal abundance, often parametrized as [Fe/H]; metals are understood to mean the chemical elements beyond H and He) and radial velocities, which can be used to derive kinematic and chemical constraints on the main structures and stellar populations of the Milky Way. What has been missing, until only recently, is the ability to assign ages to individual stellar populations, so that the full chemodynamical history of the Milky Way can be assessed.

In the case of the Galactic bulge, crude age information has been inferred from comparison with population-synthesis models⁷, while for the disk, the burgeoning field of asteroseismology provides age estimates for individual stars based on observations of their internal oscillation modes⁸. For the halo of the Galaxy, its age (and metallicity) structure was first motivated by study of the colour–magnitude diagrams for a handful of globular clusters (compact, spherical groups of hundreds of thousands to millions of stars), and used to suggest a hierarchical assembly model of the Galaxy⁹, contrasting with the rapid monolithic collapse model that was initially adopted¹⁰. In later studies with improved precision, it was demonstrated that the majority of globular clusters located within 15–20 kpc of the Galactic Centre are older (by ~2 Gyr) than most of the clusters located farther away¹¹,¹².

In the last decade, numerous studies have revealed that the stellar halo of our Galaxy is a complex system comprising at least two diffuse components with differing spatial distributions, chemistry and kinematics, the inner-halo and outer-halo populations, along with a number of individual over-densities and stellar debris streams¹³. The over-densities, such as those identified in the directions of Virgo and Monoceros, in addition to being spatially distinguishable from the diffuse components, exhibit distinct metallicity distributions and coherent motion. The debris streams, a number of which can be directly associated with parent dwarf galaxies that are in the process of being accreted by the Milky Way, such as the Sagittarius Stream¹⁴ and the Orphan Stream¹⁵, also possess distinct metallicities and kinematics. The integrated contribution from these debris streams may comprise as much as half of the stars now found in the halo system¹⁶. To understand the complete assembly process of the halo system, the ability to infer ages for the various components and structures is clearly required.

A seminal study, conducted a quarter-century ago, suggested a technique that can provide information on the ages of the stellar populations in the halo of the Milky Way based on the colours of a class of stars known as field blue horizontal-branch (BHB) stars¹⁷. Originally identified because of their distinctive position in the colour–magnitude diagrams of globular clusters, BHB stars are less massive than the Sun (0.6–0.7 M☉, ref. 20), but (owing to their larger ages) have already passed through their main-sequence (core hydrogen burning) and giant-branch stages of evolution, and are burning helium in their cores. This first study, which included some 500 field BHB stars in the range 2–12 kpc from the Galactic Centre, reported a small, but statistically significant, shift in the mean B–V colours that the authors argued was associated with a difference in age of about 2.5 Gyr, with the oldest stars found closest to the centre.

More recently, the age structure of the halo system, based on a significantly larger sample (~4,700) of field BHB stars with available spectroscopy from SDSS Data Release 8¹⁸ (DR8), has been explored¹⁹. Spectroscopic data have the great advantage that, in addition to enabling estimates of the metallicity for stars in the sample, the derived stellar temperatures and surface gravities can be used to eliminate the primary contaminant population

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occupying a similar colour range as BHB stars, the blue straggler stars (BSSs; higher-gravity stars lying blueward of the halo main-sequence turnoff region). This spectroscopically confirmed sample of BHB stars was employed to construct a low-resolution chronographic (age) map of the Galactic halo system, including stars with distances up to \( \sim 25-30 \) kpc from the Galactic Centre; the region where clear inference of age structure could be obtained was limited to \( \sim 25 \) kpc. In addition to taking into account modern models of BHB evolution to derive the dependence of BHB colours on age, this study was also able to demonstrate that the colour shift used to infer ages was not strongly correlated with changes in the metallicity of the populations, but is a clear age effect. In fact, the mean metallicity of BHB stars in the halo field is almost constant over the colour range adopted in our analysis (ref. 22, top right panel of Fig. 2).

In this article we extend these techniques by employing a large sample of \( \sim 130,000 \) colour-selected field BHB stars from SDSS. Although spectroscopic information is not available for the great majority of these stars, we use the spectroscopic identifications of BHB stars and BSSs from the previous study\(^{22}\) to specify colour ranges that minimize possible contamination from BSSs. The resulting sample is then used to construct a new, high-resolution, age map of the halo system of the Milky Way, extending to 60 kpc from the Galactic Centre. The refined map enables the identification of
numerous new over-densities and possible debris streams, measures of the decrease in the mean age and increase in the dispersion of stellar ages with distance from the Galactic Centre, and opens a pathway toward examination of the age structure within individual structures, as demonstrated below.

For a fixed chemical composition, the initial colour of a BHB star is uniquely determined by its mass; a less-massive BHB star has a bluer colour. The age–colour relation for BHB stars emerges because older stars possess lower initial masses than younger stars, while the mean mass lost during the preceding giant-branch phase was approximately equal. The change in colour of BHB stars as they evolve away from the zero-age horizontal branch does not affect our colour–age transformation, as our population-synthesis tool takes this into account when it generates the sequence of models used to calculate the mean colours of BHB stars.

The slope of the age–colour relation for BHB stars does not strongly depend on metallicity; however, its zero point does. For stars of the same initial mass, a lower metallicity star arrives on the horizontal branch with a bluer colour than a higher metallicity star; this information is not included in the present analysis. However, our mapping technique is statistical, in that we marginalize over the (unknown) metallicity of at least 10 stars in each accepted pixel in our chronographic maps. Unless the metallicities of the stars in a given pixel are strongly deviant from the expected distribution for halo stars, the derived mean colour should provide reasonable estimates of the age. This has already been demonstrated in a previous study\(^2\), which recovers similar behaviours of the change in mean colour, hence age, with Galactocentric distance for BHB stars having spectroscopically derived metallicities, \([\text{Fe/H}] > -1.75\), and those with \([\text{Fe/H}] < -1.75\). Note that small perturbations due to metallicity variations for individual structures may nevertheless exist.

The selection of our sample of BHB stars is described in the Supplementary Methods. The dependence of inferred age on colour employed in this analysis was derived by adopting a horizontal-branch stellar population-synthesis tool that provides an estimate of the age shift as a function of the mean \((g - r)\) colour shift, \(\Delta t = -16.9 \Delta (g - r) \) (where \(\Delta t\) represents the age shift in billions of years), over the colour range \(-0.30 < (g - r) < 0.00\)\(^\text{2}\).

Figure 1 shows the colour (age) maps obtained by employing the colour-selected BHB stars and the colour–age relation discussed above. In panels a and d the data are shown in the \((X,Z)\) plane, with \((0,0)\) located at the Galactic Centre \((Z\) is the vertical distance above or below the Galactic plane), where the squares in panel d represent the mean colours (and ages) of the BHB stars in a grid of 1 kpc square pixels. Panels a, b and c of Fig. 1 are constructed by applying a Gaussian kernel smooth (of width 3 kpc) to the accepted pixels in the vicinity (such as the Ancient Chronographic Sphere of stars within 15 kpc of the Galactic Centre\(^2\)). Outside this region the halo system is dominated by stellar populations with average ages of \(\sim 11\) Gyr (green colours).

It is also clear from inspection of the maps that there are numerous resolved structures present throughout the halo system, some (but not all) of which have been previously identified on the basis of their number-density contrast. Known overdensities and streams are identified by labels on the maps shown in Fig. 1; locations of these are listed in Supplementary Table 1. Many of the recognized structures are members of the northern (leading/trailing) or southern (leading/trailing) arm of the Sagittarius Stream\(^26,27\). Figure 2 is a cutout of the \((X,Z)\) plane in the region of the southern arms. According to the colour (age) coding, this portion of the stream spans a range of ages from \(\sim 9.5 \) Gyr to \(\sim 11\) Gyr, with the youngest stars concentrated in the central regions, and the oldest stars located in the outer regions. Commensurate ages for stars in this portion of the stream were derived from recent photometric and spectroscopic observations\(^23\); stars in the northern arm exhibit a similar age distribution.

We also identify a blue-coloured extended region in panel a (also visible in panels b and c) of Fig. 1 with the Virgo stellar over-density\(^29\) (labelled with a V). The colour (age) coding suggests that the underlying stellar population in the Virgo over-density appears to be old, with an age on the order of 11.5–12 Gyr. Recent studies of main-sequence stars located in the Virgo over-density suggest an age of \(\sim 9\) Gyr\(^29\), which is 2–3 Gyr younger than our estimate. However, the derived median metallicity \(\langle [\text{Fe/H}] \rangle = -0.7 \) is also substantially higher than the values reported in other recent studies, \([\text{Fe/H}] = -2.0 \) (ref. 31) and \(-1.5 < [\text{Fe/H}] < -2.5 \) (ref. 32); there remains doubts whether the same stellar population is being considered.

The yellow/orange-coloured features in panels a and b of Fig. 1 may be portions of the Styx Stream\(^3,34\) (labelled with Styx). The Orphan Stream\(^35\) is associated with a blue-coloured feature in panel a and b (labelled with an O). The Styx Stream covers a range of ages of 10–11 Gyr, while the Orphan Stream seems to be older, with an age of \(\sim 11.5\) Gyr. Panel a also shows a blue-coloured region in the Southern Galactic Hemisphere identified as a portion of the Cetus Polar Stream\(^3,37\) (labelled as CPS). According to the colour (age) coding, the stream is \(\sim 12\) Gyr old.

A yellow-coloured clump in panel b is probably a portion of the Hercules–Aquila cloud\(^39\) (labelled with HA); according to our colour (age) coding the structure has an average age of \(\sim 11\) Gyr.
Figure 3 | Colour (age) distribution of accepted pixels (containing at least 10 stars) for different ranges of the vertical distance, \( Z \). The solidblack vertical bars are proportional to the logarithm of the number of stars in each pixel. The solid orange vertical bar represents the median colour (age) for each \( Z \) range. The green-shaded areas encompass \( \pm 1 \sigma \) units of the bi-weight estimator of scale, a robust calculation of the dispersion of the data. The colour (age) dispersions and their errors ((bi-weight scale)/\( \sqrt{2N} \)) are shown in the top left of each panel. Such dispersions appear to increase with distance from the Galactic plane. The shift in median colour (age) in the Southern Galactic Hemisphere for \(-35 \, \text{kpc} < Z < -25 \, \text{kpc}\) is due to the prominent strip of older stars seen in Fig. 1. This trend is not evident in the Northern Galactic Hemisphere, and suggests an asymmetric age distribution between the two hemispheres.

There are other clumps and/or debris streams visible in panels a–c of Fig. 1 (blue or orange–yellow colours) that could not be identified with any known structures. We defer further discussion of these to a future paper, which reports on a quantitative search for detectable structures in these maps.

Although the \((X, Z)\) chronographic map exhibits a transition from older to younger stars as the vertical distance increases, the underlying age distribution is more complex, as can be appreciated from inspection of the age distributions shown in Fig. 3. The left and right columns of panels represent the regions above and below the Galactic plane, respectively. Both distributions exhibit the relative dominance of the oldest halo stars from close to the Galactic plane up to about 10 kpc, which we associate with an Ancient Chronographic Sphere that extends into regions of the halo including the solar vicinity. At larger distances from the plane the number of younger stars gradually increases, and the median age, represented by the vertical orange bars, moves progressively towards younger ages. It is also clear that the dispersion in age (shown in the upper left of each panel) increases with distance from the Galactic plane. Between 3 kpc and 30 kpc, the median stellar age shifts from \(\sim 11.5 \, \text{Gyr}\) to \(\sim 11.1 \, \text{Gyr}\), yet the oldest stars remain present at all distances. This trend suggests that as one goes outward from the Galactic Centre the number of younger structures progressively increases, and that these spatially distinct systems become a significant part of the halo system at distances exceeding 30 kpc. Figure 4 summarizes the variations in the mean ages of halo stars with distance in the vertical and radial directions.

Previous studies of globular clusters in the Milky Way showed that the morphology of the colour distribution of cluster horizontal-branch (HBB) stars depends on the cluster metallicity, in the sense that metal-rich clusters ([Fe/H] \(> -0.8\)) typically exhibit very red HBs, while metal-poor clusters have different HB colour distributions, even at fixed metallicity\(^1\). This characteristic suggested that there is a second parameter, probably the cluster’s age, which influences the HB morphology. The second parameter is strongly correlated with Galactocentric distance (younger clusters being found at larger distance, beyond \(\sim 40 \, \text{kpc}\)), and the scatter in HB morphology increases with increasing distance\(^9\). In other words, the age dispersion of globular clusters in the Milky Way’s halo increases as the distance increases, in agreement with our finding for field stars in the diffuse halo, when age is assumed as the second parameter.

Contemporary lambda cold dark matter theories of structure formation predict that galaxies formed from the hierarchical accretion and mergers of proto-galactic systems\(^3\). Numerical simulations of this process, which describe the joint evolution of baryons and dark matter, predict that the oldest stellar populations are mainly concentrated in the inner regions of the resulting haloes, with tightly bound orbits\(^40\). This is a natural consequence of the inside-out assembly of haloes, whereby progenitor haloes with a distribution of masses formed at early times and combined to assemble larger fragments, which in turn merged to form the primary halo of a galaxy. Some of the stars now found in the inner regions of galaxies were born in these proto-galactic systems (or fragments) and then became part of the main galaxy halo by merging and accretion (accreted stars), while others were born from infalling gas mainly associated with progenitor galaxies \((in \, situ)\) stars\(^42\).

The chemical evolution of lower-mass fragments is expected to be truncated due to either the consumption of all of the available gas, or the expulsion of gas by massive-star supernova explosions,
Figure 4 | Colour (age) gradient in the vertical distance and in the radial distance directions. The red squares denote the mean colour for each 1 kpc bin in distance (left Y axes) and the grey line represents a linear regression to the data. The right Y axes shows the mean age. a, Colour (age) gradient and its error above the Galactic plane. b, Colour (age) gradient and its error below the Galactic plane. The data indicate that the underlying stellar populations become progressively younger with distance from the Galactic plane, with a slope of $-13.9 \pm 0.8$ Myr kpc$^{-1}$ in the Northern Galactic Hemisphere and $-16.1 \pm 1.6$ Myr kpc$^{-1}$ in the Southern Galactic Hemisphere, respectively. The mean values in the range of $-35$ kpc $< Z < -25$ kpc are slightly displaced from the regression line, as discussed in Fig. 3. c, Colour (age) gradient over radial Galactocentric distance, $R$, with a slope $-25.1 \pm 1.0$ Myr kpc$^{-1}$. The error on the colour (age) gradient in each panel is the standard deviation of the slope of the linear regression line.

after only a limited amount of star formation has taken place (other quenching mechanisms include tidal stripping and reionization). This quenching probably occurred before these clumps merged with the rest of the proto-galaxy; hence, they primarily contribute to the oldest stellar populations in the halo system.

In the case of more-massive fragments, the star-formation process is expected to progress further due to the larger initial gas content and the relatively deeper potential wells, which can retain gas even in the presence of multiple generations of star formation. In such environments, star formation is expected to halt only when these fragments begin to merge, or undergo later dissipational interactions with the proto-galaxy that result in either the stripping or shock-heating of the remaining gas.

A simple scenario for the formation of stellar haloes based on two different clocks can be envisaged, to understand the results shown in Fig. 3—a chemical-evolution clock that operates within each progenitor sub-halo that depends on their physical properties (gas fraction, star-formation rate) and an accretion clock that tracks the assembly process within a cosmological context. Fig. 3 could be understood with this picture, where both very old stars and younger stars populate the regions in different proportions as a function of distance from the Galactic plane.

The presence of multiple stellar populations in the haloes of galaxies (often referred to as the diffuse inner- and outer-halo populations) is a general feature of current numerical simulations of galaxy formation$^{42-44,46,47}$, and places the observational results that have revealed such populations in the Milky Way$^{48-53}$, M31$^{54}$ and other galaxies$^{55}$ on firmer theoretical footing. According to these models, the inner-halo population stars might have formed with a significant contribution from more-massive sub-haloes (with sustained star formation), or formed in situ in the inner region from the rapid collapse of infalling gas. In contrast, a larger fraction of stars of the outer-halo population formed in lower-mass dwarf galaxies, and were brought into the main halo through disruption and accretion, resulting in a diffuse outer halo with distinct and significantly hotter kinematics. Merger events may also produce features such as debris streams that contribute relatively younger stars. One would expect to find samples of old stars arising from both populations present in the Solar Neighbourhood.

The new detail shown in our high-resolution chronographic map clearly indicates that younger structures dominate the outer region of the halo system; these structures are expected to arise from late-term ($<5$–10 Gyr) merging events. The low-density outer region of the diffuse halo system is probably not as effective in erasing the signatures of such mergers, as there was not sufficient time for them to phase-space mix with the rest of the outer-halo stars already in place. Other observational studies show that these systems are typically more metal rich than the diffuse components ($\langle \mathrm{Fe/H}\rangle > -1.5$), and dominate the Galactic halo system at distances exceeding 30 kpc; the presence of the diffuse components at these distances is clearly evident in the observed metallicity distributions of K giants$^{18}$, which exhibits peaks at $[\mathrm{Fe/H}] \sim -1.3$ (structures), $[\mathrm{Fe/H}] \sim -1.6$ (inner halo) and $[\mathrm{Fe/H}] \sim -2.3$ (outer halo).

Our technique for estimation of the age distribution for stellar populations in the halo of the Milky Way can be readily extended to new photometric samples assembled by numerous contemporary and future surveys, as well as to other large galaxies in the Local Group such as Andromeda and the Magellanic Clouds. Refinement of the technique to include a full grid of the variation in observed colours of BHB stars with metallicity, as well as age, is underway, and should prove useful for detailed analysis of the age structure of individual over-densities, debris streams and dwarf galaxy satellites of the Milky Way.
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**Author contributions**

D.C., T.C.B., V.M.P., R.M.S., G.L. and Y.S.L. performed the analysis and interpretations of the observations. The chronographic maps were assembled on the basis of graphical techniques developed by V.M.P. P.D. carried out modelling of the mapping of BHB colours to age estimates. D.C., T.C.B., P.B.T. and J.T. carried out comparisons of the results with expectations from numerical simulations of galaxy formation. All authors discussed the results and commented on the manuscript.

**Additional information**

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**Competing financial interests**

The authors declare no competing financial interests.