The total stellar halo mass of the Milky Way

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ABSTRACT
We measure the total stellar halo luminosity using red giant branch (RGB) stars selected from Gaia data release 2. Using slices in magnitude, colour and location on the sky, we decompose RGB stars belonging to the disc and halo by fitting 2-dimensional Gaussians to the Galactic proper motion distributions. The number counts of RGB stars are converted to total stellar halo luminosity using a suite of isochrones weighted by age and metallicity, and by applying a volume correction based on the stellar halo density profile. Our method is tested and calibrated using Galaxia and N-body models. We find a total luminosity (out to 100 kpc) of $L_{\text{halo}} = 8.9 \pm 2.2 \times 10^8 L_\odot$ excluding Sgr, and $L_{\text{halo}} = 10.0 \pm 2.5 \times 10^8 L_\odot$ including Sgr. Assuming a stellar mass-to-light ratio appropriate for a Kroupa initial mass function ($M^*/L = 1.5$), we estimate a stellar halo mass of $M^*_{\text{halo}} = 1.5 \pm 0.4 \times 10^9 M_\odot$. This mass is larger than previous estimates in the literature, but is in good agreement with the emerging picture that the (inner) stellar halo is dominated by one massive dwarf progenitor. Finally, we argue that the combination of a $\sim 10^9 M_\odot$ mass and an average metallicity of $\langle [\text{Fe/H}] \rangle \sim -1.5$ for the Galactic halo points to an ancient ($\sim 10$ Gyr) merger event.

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

1 INTRODUCTION

The halo of our Galaxy is littered with the stellar debris of destroyed dwarf galaxies. This trash-can of material extends out to several hundred kiloparsecs, and gives important insight into the assembly history of the Milky Way and its dark matter potential. Moreover, the remains of the destroyed dwarfs can tell us about the properties of the lowest mass galaxies in the Universe.

The content, size, extent, and kinematics of the stellar halo has been studied extensively over the past few decades (see reviews by Helmi 2008; Belokurov 2013). In particular, the number counts of old and relatively metal-poor stars have revealed that the density profile of the stellar halo approximately follows a power-law with index $\sim -2.5$ within 20 kpc, and then falls-off more rapidly thereafter, with power-law index $\sim -4.0$ (e.g. Watkins et al. 2009; Sesar et al. 2010; Deason et al. 2011; Faccioli et al. 2014; Pila-Díez et al. 2015). This change in density at $\sim 20$ kpc profile signifies a transition between the “inner” and “outer” halo. Deason et al. (2013) argued that this broken profile is caused by the accretion of a massive dwarf galaxy at early times. In this scenario, the break radius represents the last apocentre of the accreted dwarf, and beyond this furthest point of the orbit, the contribution of the debris from this massive dwarf is significantly diminished. Thus, this picture suggests that the inner stellar halo is dominated by one massive accretion event, while the outer halo is a dusting of several (lower-mass) destroyed dwarfs.

The arrival of the Gaia (Gaia Collaboration et al. 2016a) data releases (Gaia Collaboration et al. 2016b, 2018a), which provide 6-dimensional phase-space measurements for thousands of local halo stars, and proper motion measurements for hundreds of thousands of halo stars, reinvigorated our ideas about the structure of the halo, and confirmed the insight we gained from the halo number counts. In particular, Belokurov et al. (2018), Haywood et al. (2018) and Helmi et al. (2018) used a combination of kinematical and chemical data from Gaia, SDSS and APOGEE to find that the inner halo is indeed dominated by one massive accretion event, which occurred $\sim 8$ Gyr ago. This significant event in the history of the Galaxy has been dubbed the Gaia-Sausage (aptly named due to it’s highly eccentric orbit) or Gaia-Enceladus. Follow-up studies have added extra weight to the growing consensus that the Gaia-Sausage rules the (inner) halo: for example, Deason et al. (2018) and Lancaster et al. (2019) used the kinematics of distant halo stars to dynamically show the transition at $\sim 20$ kpc between the “Sausage” dominated regime and the outer halo, and Myeong et al. (2018), Myeong et al. (2019) and Massari et al. (2019) used the dynamics of the globular cluster population in action space to show that many are likely related to the Gaia-Sausage, as expected if this is a massive merger event.

As mentioned above, the density profile of halo stars has proved an invaluable measure to constrain the Galaxy’s assembly history. However, the normalisation of the density profile, and
hence the total stellar halo mass, has proven to be more complicated to measure. This is mainly because the tracers we often use to map the halo star distribution out to large distances, i.e. the RR Lyrae and blue horizontal branch stars, are difficult to relate to the overall halo population. This is because the exact broad-band color (and hence temperature) distribution of the helium burning stars depends on additional “hidden” parameters (see e.g. Gratton et al. 2010).

Moreover, it is difficult to provide a robust normalisation when using surveys that have non-trivial selection functions and/or are limited in their spatial extent. Most measures of the total stellar halo density are limited to local halo star samples, and a wide range of density normalisations have been quoted in the literature: \( \rho_0 = 3.0 - 15.0 \times 10^{-5} M_\odot/pc^3 \) (e.g. Morrison 1993; Fuchs & Jahreiß 1998; Gould et al. 1998; Digby et al. 2003; Juric et al. 2008; de Jong et al. 2010). Many of these measures were estimated before the density profile out to large distances was known, and hence relating the local stellar density to the total stellar halo mass is non-trivial. More recently, Bell et al. (2008) estimated the total stellar mass using main sequence turn-off stars in SDSS, and Deason et al. (2011) used counts of blue horizontal branch stars in SDSS. Both these studies favour relatively low stellar halo masses \( M_{\text{halo}}^{*} \sim 3 - 4 \times 10^{8} M_\odot \), but there is sizeable uncertainty relating these tracer populations to the overall stellar halo (see above). In addition, these measures do not include the few \( \sim 10^{8} M_\odot \) substructures in the halo, which also contribute to the mass, so the total mass, based on the Bell et al. (2008) and Deason et al. (2011) estimates for the “field” halo, is in the range \( M_{\text{halo}}^{*} \sim 4 - 7 \times 10^{8} M_\odot \) (cf. Bland-Hawthorn & Gerhard 2016).

Currently, different estimates of the Galactic stellar halo mass vary by a factor of 2, but, more worryingly, the uncertainty of these estimates is not robustly quantified. Perhaps more puzzling is that the recent deluge of evidence for a massive accretion event dominating the stellar halo, appears at odds with the rather low value of total stellar halo mass quoted in the literature. Rectifying this apparent conundrum is crucial in order to place the Milky Way in the cosmological context with other, similar mass galaxies. Both simulations and observations show that at fixed galaxy (or halo) mass the range of stellar halo masses is large, reflecting a wide diversity of assembly histories (e.g. Pillepich et al. 2014; Merritt et al. 2016; Harnsen et al. 2017; Elias et al. 2018; Monachesi et al. 2019). Moreover, work by Deason et al. (2016) and D’Souza & Bell (2018) show that the stellar halo mass is critically linked to the most massive dwarf progenitor of the halo. Thus, in order to reconcile several global properties of the Milky Way...
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h in the halo (e.g. density profile, metallicity) with the currently favoured assembly history scenario, it is imperative that we procure a robust total stellar halo mass, complete with a well-defined uncertainty.

In this paper, we utilise the exquisite data from Gaia to estimate the total stellar halo luminosity and mass using red giant branch (RGB) stars. Compared to previous work, we take advantage of the full sky coverage of the Gaia survey, and use the proper motion distributions to decompose disc and halo populations. In Section 2 we describe the selection of RGB stars, and introduce the models that we use to guide and calibrate our analysis. Number counts of halo stars are estimated in bins of colour, magnitude and area on the sky, and our process for decomposing the disc and halo populations is described in Section 3. In Section 5 we determine how well this procedure performs on N-body stellar halo models. We discuss our resulting stellar halo mass in Section 5, and summarise our main conclusions in Section 6.

2 HALO RED GIANT BRANCH STARS

Our aim is to use counts of halo red giant branch (RGB) stars to estimate the total stellar halo luminosity. RGB stars are ideal tracers for this purpose as they are intrinsically bright, relatively numerous, and are present at all ages and metallicities. Moreover, we are able to cleanly select RGB stars using Gaia data (see below). In order to guide us through the stellar halo selection and luminosity estimate, we make use of “toy” models of the Galaxy, which are tailored towards the Gaia data release 2 (GDR2) astrometry and photometry.

2.1 Galaxia and N-body models

We use the Galaxia model (Sharma et al. 2011) to create a synthetic survey of the Milky Way. We choose the default (analytical) Galaxia model for the disc population (the Besançon model, Robin et al. 2003), and the Bullock & Johnston (2005) (BJ05) N-body models for the stellar halo. Galaxia employs a scheme to sample the N-body models, which ensures that the phase-space density of the generated stars is consistent with that of the N-body particles. There are eleven stellar halo models, each representing a different assembly history and stellar halo mass. This suite of simulated stellar haloes has been used extensively in the literature (e.g. Bell et al. 2008; Xue et al. 2011; Deason et al. 2013), and although there may be limitations relative to more sophisticated cosmological simulations, they are an incredibly useful tool for testing and calibrating observational survey data.

The BJ05 models only include halo stars from accreted dwarf galaxies, there are no halo stars born “in-situ” in the parent halo, as predicted by cosmological hydrodynamic simulations (e.g. Zolotov et al. 2009; Font et al. 2011). However, if this population does exist (this is still not clear in the Milky Way: Deason et al. 2017; Belokurov et al. 2018; Di Matteo et al. 2018; Haywood et al. 2018) it is likely confined to the inner halo and will have similar properties to the thick disc (Zolotov et al. 2009; McCarthy et al. 2012; Pillepich et al. 2014; Gallart et al. 2019). Thus, in our decomposition of halo/disc populations (see Section 3) any in-situ halo stars will likely be labeled as disc stars. However, we cannot exclude the possibility that some fraction of the stellar halo mass

Figure 3. The mean (first and third panels) and dispersion (second and fourth panels) of the Galaxia model proper motions as a function of $BP - G$ colour. Blue and red lines indicate the halo and disc components, respectively. Different magnitude bins are shown with different line styles, and each row shows a different bin in Galactic longitude. The sequences are very similar for bins above and below the Galactic plane, except for $(\mu_b, \mu_l)$ (third column), which we indicate with different shades of blue and red. The last panel on the right indicates the fraction of halo stars as a function of colour.
we compute in the Gaia data has an in-situ origin. This is discussed further in Section 5.

A synthetic survey is produced from the models in Johnson-Cousins bandpasses and converted to the Gaia photometry using the relations given in Jordi et al. (2010). Uncertainties in photometry and astrometry applicable to GDR2 are also included in the model. This is implemented using the Python PyGAIA package1. This module implements the performance models for Gaia which are publicly available2.

In the left-hand panel of Fig. 1 we show a colour-magnitude diagram (CMD) for high latitude (|b| > 30°) red stars in the Galaxia model. Here, we consider stars with \( G_{BP} - G_{RP} > 1.0 \) and \( 14 < G < 17 \). The dashed lines indicate the colour range we consider for RGB stars. In the middle panel, we exclude stars with parallax > 0.2 (approx. \( D < 5 \) kpc). This cut removes the nearby dwarf stars, but there are still disc giants present. We indicate the disc and halo populations with the red and blue contours, respectively. We have checked that the completeness of the halo star sample is not significantly affected by the parallax cut. We find that, for the magnitude and colour range under consideration, the halo stars with \( D > 5 \) kpc are complete to \( \geq 90\% \). Our selection of RGB stars, based on magnitude, colour and parallax, spans the distance range \( D \sim 5 - 100 \) kpc. In the right-hand panel of Fig. 1 we show the proper motions of the RGB stars in Galactic coordinates \((\mu_l, \mu_b)\). The disc and halo components are indicated with the red and blue contours, respectively. The disc and halo components have distinct, but overlapping, proper motion distributions. Here, we are showing all stars across the sky, but these sequences vary depending on the Galactic coordinates (see Fig. 3). This figure shows that the proper motion distributions of RGB stars can be used to disentangle the disc and halo populations. In Section 3 we use the proper motion distributions to estimate the number of RGB stars in the halo in bins of colour, magnitude and position on the sky.

2.2 Gaia DR2

The models described in the previous sub-section are tailored towards the GDR2 dataset. Before going further, we briefly describe our selection of the real Gaia data. We select stars from GDR2 with photometry, parallax, and proper motion information. The photometry is corrected for extinction using the Schlegel et al. (1998) dust maps, and we use the relations given in Gaia Collaboration et al. (2018b) to correct the \( G, G_{BP} \) and \( G_{RP} \) bandpasses. We only include stars with re-normalised unit weight error, RUWE < 1.4 (Lindegren 2018), which ensures stars with unreliable astrometry are excluded. In addition, we exclude stars with large BP/RP flux excess using the selection given in Gaia Collaboration et al. (2018b). These cuts remove ~ 8% of the sample in the colour, magnitude and latitude range under consideration (see below). Note

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1 https://pypi.org/project/PyGaia/
2 http://www.cosmos.esa.int/web/gaia/science-performance
most of the star excised are at the fainter, redder region of our selection. From the cleaned sample, we select RGB stars at high latitude ($|b| > 30^\circ$) with parallax $< 0.2$, $1.0 < G_{BP} - G_{RP} < 1.6$ and $14 < G < 17$ (see Fig. 1).

In the following Section, we decompose the disc and halo RGB stars using proper motion information. First, we illustrate this process using the Galaxia models, and we then apply the technique to our GDR2 sample.

### 3 DISC-HALO DECOMPOSITION

In Fig. 1 we showed that our selection of RGB stars includes both halo and disc populations. In order to disentangle these populations, we use the 2-dimensional proper motion distributions. We assume 2-D (for each component of proper motion) Gaussian distributions for both the halo and disc. This Gaussian approximation is reasonable as we (independently) fit in bins of magnitude, colour and position on the sky, rather than fit the entire distribution with one 2-D Gaussian. We use 6 bins in magnitude (between $14 < G < 17$), 6 bins in colour (between $1.0 < G_{BP} - G_{RP} < 1.6$), and 8 spatial bins. The spatial bins are shown in Fig. 2. When applying this method to the Gaia data we exclude stars within 30 deg of the LMC and 10 deg of the SMC. We also perform the analysis both with and without stars in the vicinity of the Sagittarius (Sgr) stream. The Sgr stars are selected to lie within 12 degrees of the tracks shown in Fig. 2 (see Deason et al. 2012; Belokurov et al. 2014).

In Fig. 3 we show the true Gaussian parameters for the disc and halo populations in the Galaxia model. For this illustration the halo component is Halo-7, although similar trends are seen in all of the haloes. This figure shows that the overlap between the disc and halo components varies as a function of magnitude, colour and position on the sky. In some cases the overlap is larger, and in others the populations are more distinct. To perform the fits simultaneously (i.e. without knowing which stars belong to disc or halo), we model the proper motion distributions with a mixture of two (halo+disc) multi-variate Gaussians using the Extreme Deconvolution algorithm described in Bovy et al. (2011). In Fig. 4 we show the outcome of these fits for the Galaxia model. Note that we initialise the fits using the true Gaussian values for the disc and a halo model (Halo-7 in this case). This step is taken to avoid misclassification of the halo/disc components. However, we check that initialising with different halo profiles, or an independent disc model makes little difference to the results (see later). Fig. 4 shows that in some bins the decomposition works well, while in others we are unable to clearly distinguish the distinct components. We note the true and fitted halo amplitudes (number of halo stars) in the bottom right corner of the panels. Bins at redder colours and fainter magnitudes have little, if any, disc component so the fits are straightforward. However, even with a significant disc contribution (e.g. at bluer colours, and brighter magnitudes) we can sometimes get good estimates of the halo amplitudes.

The reliability of the decomposition for each bin is illustrated in Fig. 5. Here, we show the relative difference between the estimated and true number of halo stars. We have combined results from all eleven BJ05 haloes and show the median and 16/84 percentiles. In certain bins, our estimates are poor (over/under estimate by more than 30 percent) and these are shown with black crosses. These are cases where the overlap between disc and halo makes decomposition based on proper motion alone very difficult. However, in most of the bins (70 percent) we are able to recover the true number of halo stars to within 30 percent. When we apply this method to the Gaia data we can exclude the bins with significant systematics.

In Fig. 6 we show examples of the 2D Gaussian fits to the Gaia data. These example bins are the same as in Fig. 4. We show the more general results in Fig. 7. Here, we can see the resulting Gaussian parameters behave similarly to the model predictions (shown in Fig. 3). We note that a noise component becomes apparent in the faintest bins ($16.0 < G < 17$), which is labeled as “disc”. This component is relatively minor, as the number of stars belonging to the disc in the faint, red bins is very low ($N \lesssim 50$). Moreover, in all bins, the halo component appears to be well-behaved, which gives us confidence that our estimated halo amplitudes are reasonable.

To provide error estimates on the number of halo RGB stars in each bin, we perform the fits $N = 100$ times. Before each fit, we scatter the parallax according to the error distribution and then make a cut of parallax $< 0.2$. In addition, we randomly select one of the eleven BJ05 haloes to initialise the fits. As a final check, we initialise the disc parameters using a completely independent
model to Galaxia. For this we use the disc model described in Sanders & Binney (2015). This model has an action distribution that varies smoothly with age and metallicity using analytic prescriptions for dynamical heating, radial migration and the radial enrichment of the interstellar medium over time. A mock catalogue on on-sky position, magnitude, age, metallicity, mass and velocities was generated using Markov Chain Monte Carlo sampling (Foreman-Mackey et al. 2013) of the model combined with a set of PARSEC isochrones. We require samples to have $14 < G < 17$ and $1 < (G_{\text{BP}} - G_{\text{RP}}) < 1.6$, and convolve the output samples in parallax, proper motion and magnitudes using nearest neighbours in magnitude and on-sky position from GDR2. We find that, after initialising the disc component using the Sanders & Binney (2015) model, the resulting halo amplitudes are very similar, and do not significantly affect our derived luminosity (see following section).

### 4 TOTAL STELLAR HALO LUMINOSITY

In the previous Section, we calculated the number of halo RGB stars in bins of colour, magnitude and regions on the sky. We now want to convert these numbers into an estimate of the total stellar halo luminosity (and hence stellar mass). We provide a luminosity estimate for each bin, by applying the following two corrections:

(i) **Stellar population correction:** We use isochrones to relate the number of RGB stars in a given colour bin to the total luminosity. Here, we use the PARSEC isochrones (Bressan et al. 2012), with metallicities in the range $-2.5 < [\text{Fe/H}] < 0.0$ and ages 10-14 Gyr. For each isochrone, we calculate the number of RGB stars per unit luminosity as a function of colour. We adopt the PARSEC isochrones as our “fiducial” stellar population model (these are also the models used in Galaxia), and we comment on the changes to our results when other models are used in Section 5. For each of our 6 colour bins (with 0.1 dex width) we calculate $N_{\text{RGB}} / L_\odot$. This procedure requires us to assume an initial mass function (IMF):

$$\frac{N_{\text{RGB}}}{L_\odot} = \frac{\int_{m_1}^{m_2} \xi(m) \, dm}{\int_{m_{\text{min}}}^{m_{\text{max}}} \xi(m) \, dm} \quad (1)$$

where, $\xi(m)$ is the IMF and $i$ denotes the isochrone. The limits $m_1$ and $m_2$ give the mass range probed by a particular colour bin, and $m_{\text{min}}, m_{\text{max}}$ denotes the full range of masses probed by the isochrone. Note that the luminosity estimate is only weakly dependent on the IMF, as most of the commonly used IMF parameterizations are very similar for the high mass stars, which dominate the stellar light. In comparison, the stellar mass strongly depends on the adopted IMF, as the uncertainty of the mass function for low mass stars, which dominate the mass, is significant. It is for this reason that we provide a robust estimate of total stellar luminosity, rather than mass. This luminosity can later be converted to stellar mass using the appropriate stellar mass-to-light ratio for a given IMF (see Section 5). For the Galaxia models we use a Chabrier IMF (Chabrier 2003, as assumed for the halo’s N-body component.
in this model), and we use the Kroupa IMF (Kroupa 2001) when estimating the Milky Way halo luminosity using *Gaia* data. In practice, these IMFs are comparable and give very similar luminosity (and mass) estimates.

We next convert $N_{\text{RGB}} / L_\odot$ for each isochrone into an overall estimate by weighting the isochrones using a metallicity distribution function and age distribution. For the *Galaxia* models we fit a Gaussian to the true MDF of the halo, and for the *Gaia* data we adopt an MDF from the literature with $\mathcal{E}([\text{Fe/H}]) = 1.5$, $\sigma([\text{Fe/H}]) = 0.5$ (An et al. 2013; Zuo et al. 2017). For the ages, we assume a uniform age distribution in the range 10-14 Gyr. The top panel of Fig. 8 shows the resulting (weighted) $N_{\text{RGB}} / L_\odot$ for each colour bin. The error bars indicate the 16/84 percentiles given the adopted MDF and age distribution. We now have a way to relate total number of RGB stars in a colour bin to the luminosity. However, our estimates from the previous section are in bins of magnitude and area on the sky, and thus each probe a different volume of the halo. Thus, the final correction is to volume correct each bin.

(ii) Volume correction: Each bin in magnitude, colour and region of the sky probes a different volume of the halo. Thus, to correct our estimated number of halo RGB stars to total number of RGB stars we need to volume correct. This requires adopting a density profile for the stellar halo. This has been measured for the Milky Way in previous work, and we adopt an Einasto profile when applying to the *Gaia* data, with $n = 1.7$, $R_e = 20$ kpc and minor-to-major axis ratio $q = 0.6$ (Deason et al. 2011). For the *Galaxia* models we fit an Einasto profile directly to the halo stars out to 100 kpc. For all eleven haloes, the values typically lie in the range: $n = 1 - 5$, $R_e = 15 - 40$ kpc and $q = 0.4 - 0.8$. Our volume correction relates the volume probed by each bin to the total volume, which we assume goes out to 100 kpc. Hence, our luminosity estimates are within 100 kpc, although this is more or less identical to the total luminosity as there is very little stellar halo mass beyond 100 kpc. We use the PARSEC isochrones to calculate the distance range probed in each bin, and by adopting a density profile this can be converted into a volume:

$$
\text{Vol,}_i,\text{Total Vol} = \int_{R=0}^{R=100\text{kpc}} \int_{b=30^\circ}^{b=90^\circ} \int_{\ell=0^\circ}^{\ell=360^\circ} \rho(D, \ell, b) D^2 \cos(b) \, dD \, db
$$

(2)

where, $i$ denotes an individual isochrone and $D_1, D_2, \ell_1, \ell_2, b_1, b_2$ denote the range in distance and area probed by each bin (where the minimum value of $D_1 = 5$ kpc). The combined estimates are then calculated by weighting the isochrones by an MDF and age distribution. In the bottom panel of Fig. 8 we show this volume correction for one bin in $\ell$ and $b$ as a function of magnitude and colour.

After applying the corrections outlined above we can estimate the total stellar halo luminosity. First, we test the method on the *Galaxia* models, for which we know the true halo luminosity. In Fig. 9 we show the estimated luminosity for every bin in colour ($x$-axis), magnitude (panel) and area on the sky (coloured symbols) for three example haloes. The light grey region indicates the combined estimate for all bins, and the dark grey region indicates the combined estimate for selected bins. These selected bins are identified in the previous section, and exclude bins where the overlap between disc and halo prevents a good estimate of the number of halo RGB stars. Here, approximately 30% of the bins are excluded and
these are indicated with the black crosses in the figure. The black dashed line indicates the true halo luminosity (out to 100 kpc). The luminosity estimates in each bin have large error bars, but the combination of a large number of these bins can give a ~5% measure (but note this error is just statistical!). Reassuringly, the estimates in different bins generally agree very well, apart from the bins that we have already identified as having systematic differences (black crosses).

The results for all eleven of the BJ05 haloes are shown in Fig. 10. Here, we show the estimated luminosity relative to the true luminosity. The grey filled circles show the combined estimates from all bins, and the blue filled circles show the combined estimates from a subset of “robust” bins. The luminosity is typically underestimated by 20% when all bins are used. This is because for certain bins the halo and disc populations cannot be properly decomposed. However, if we disregard these bins we are able to recover the true value to within 25%. Note the scatter across all eleven haloes is larger than the individual statistical error bars (~5%). This is due to systematic effects, such as substructure, non-gaussian MDFs, non-Einasto density profiles etc. So, this exercise gives us a more robust estimate of the error of our estimated luminosity.

We now apply our procedure to the *Gaia* data and show the results for the luminosity estimate in Fig. 11. Here, we have performed the analysis both with and without the Sgr stream. When the Sgr stream is included the estimated luminosity increases by 10%. It is clear that including Sgr enhances the halo luminosity, particularly in the fainter, redder bins. This is particularly evident in the $\ell \in [270, 360]$, $b \in [30, 90]$ bin, which is where the apocentre of the Sgr leading arm (at $D \sim 50$ kpc) is dominant. These results give a rough estimate of the Sgr luminosity of $L_{\text{Sgr}} \sim 1.1 \times 10^8 L_\odot$, in good agreement with the value derived by Niederste-Ostholt et al. (2012). Owing to the systematics we deduced in the previous section we use a subset of bins to calculate our best luminosity estimate. We find $L_{\text{halo}} = 8.9 \pm 2.2 \times 10^8 L_\odot$ excluding Sgr, and $L_{\text{halo}} = 10.0 \pm 2.5 \times 10^8 L_\odot$ including Sgr. Here, we have assumed, based on comparison to N-body models, that this estimate is accurate to 25%. Note that if we had used all available bins, our estimates are reduced by ~10%, and the statistical error is smaller. However, as shown in Fig. 10, the systematic error increases, and the mass is likely underestimated when all bins are used.

5 DISCUSSION

5.1 A relatively high Galactic stellar halo mass?

In the preceding Section(s) we have used counts of RGB stars in GDR2 to estimate the total luminosity of the Galactic halo. This can be converted to a stellar mass by adopting an appropriate stellar mass-to-light ratio. Using the (weighted) suite of PARSEC isochrones described earlier (with uniform ages between 10–14 Gyr, and an MDF with $\langle [\text{Fe}/\text{H}] \rangle = -1.5$), we estimate stellar mass-to-light ratios of 1.3, 1.5 and 2.7 for a Chabrier, Kroupa and Salpeter (Salpeter 1955) IMF, respectively. Thus, our estimated stellar masses lie in the range: $M^*_{\text{halo}} = 1.1–2.4 \times 10^9 M_\odot$ (exc. Sgr) and $M^*_{\text{halo}} = 1.3–2.8 \times 10^9 M_\odot$ (inc. Sgr). Alternatively, we can express these values in terms of the local stellar halo density: $\rho_0 = 6.6–13.9 \times 10^{-3} M_\odot/\text{pc}^3$ (exc. Sgr), $\rho_0 = 8.0–16.8 \times 10^{-3} M_\odot/\text{pc}^3$ (inc. Sgr).

Our stellar halo mass (and luminosity) estimate is also dependent on the suite of isochrones used in the analysis, as the predictions for the RGB can vary between different stellar population models (see e.g. Hidalgo et al. 2018). If we repeat our analysis with the MIST (Choi et al. 2016) or BaSTI (Hidalgo et al. 2018) models, we find (total) stellar masses of $M^*_{\text{halo}} = 0.8–1.6 \times 10^9 M_\odot$ and $M^*_{\text{halo}} = 1.1–2.1 \times 10^9 M_\odot$, respectively. These masses are slightly lower than our fiducial results (based on the PARSEC isochrones), but still consistent within the uncertainties. The complexities of modeling the RGB in isochrone libraries is beyond the scope of this paper, but this, in addition to the IMF, is an important consideration for stellar halo mass estimates, and will need close attention in future work to achieve both precise and accurate measures.

Our estimated stellar mass is significantly higher than recent values in the literature. For example, Bell et al. (2008) and Deason et al. (2011) find masses $M^*_{\text{halo}} = 3–4 \times 10^8 M_\odot$, which is a factor of 3 lower than our estimate. However, these measurements, which use turn-off stars (Bell et al. 2008) and blue horizontal branch (Deason et al. 2011) as tracers, have considerable uncertainty from converting counts of these stars to total stellar mass (as pointed out by the authors). On the other hand, our estimate is

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**Figure 8.** Top: The relation between total luminosity and number of RGB stars per colour bin. Here, we have used a set of weighted PARSEC isochrones assuming uniform ages in the range 10-14 Gyr, and a metallicity distribution with $\langle [\text{Fe}/\text{H}] \rangle = -1.5$, or $\langle [\text{Fe}/\text{H}] \rangle = 0.5$. Bottom: The total volume (out to 100 kpc) relative to the volume probed by a colour bin. Different linestyles correspond to different magnitude bins. Here, we used the weighted isochrones to estimate the distance range probed by a specific colour, magnitude bin, and we use the stellar halo density profile to relate the volume probed to the total volume. For the Milky Way, we assume an Einasto profile with $n = 1.7$, $R_e = 20$ kpc and a minor-to-major axis ratio $q = 0.6$ (Deason et al. 2011).
Figure 9. The estimated (total) stellar halo luminosity as a function of colour. Each panel shows a different magnitude bin. For each colour, magnitude bin, there are 8 bins on the sky. The colour coding is the same as in Fig. 2. We show three example haloes from the Galaxia+N-body models. The dashed black line shows the true value, and the (light) shaded grey region indicates the combined estimate from all of the colour, magnitude and \((l, b)\) bins. The dark shaded grey region indicates the combined estimated when 30 percent of the bins (shown with black crosses) are excluded.

Figure 10. The estimated luminosity for the Galaxia+N-body haloes relative to the true values as a function of stellar halo luminosity. Here, the “total” luminosity is defined within 100 kpc. The right-inset panel shows the PDF for the \(L_{\text{halo, est}}/L_{\text{halo, true}}\) values. The grey points are the estimates when all bins are used, and the blue points are when bins with high levels of contamination are excluded. For the majority of haloes we can recover the true value to within \(\sim 25\%\). An outlier (halo-10) is indicated with a red circle; this halo has significant contribution from unrelaxed substructure.

closer to the “classical” stellar halo mass given in Morrison (1993) of \(\sim 10^8 M_\odot\).

We can also explore how some of the assumptions made to derive the stellar halo luminosity could lead to a systematic over- (or under) estimate. First, we adopt a flattened Einasto stellar halo density profile from Deason et al. (2011) to volume correct the RGB star counts in magnitude, colour and spatial bins. Although different in detail, the form of the density profile of halo stars within 50 kpc from various sources in the literature are in good agreement (e.g. Sesar et al. 2010; Facioli et al. 2014; Pilà-Díez et al. 2015; Xue et al. 2015; Hernitschek et al. 2018). Moreover, if the density profile we adopted was significantly wrong, we would see systematic variations between magnitude bins. Indeed, from inspection of Fig. 11 there is generally good agreement between different magnitude slices. Second, we adopt a MDF for the halo with \([\text{Fe/H}] = -1.5\). A change in this MDF will affect how the isochrones of different metallicities are weighted. For example, if we adopt a higher, on average, metallicity, the derived stellar luminosity is lower (e.g. a 0.5 dex increase in metallicity leads to a \(\sim 20\%\) reduction in luminosity). This is simply due to changing the absolute magnitudes of the RGB stars. However, our estimated uncertainties are \(\sim 25\%\), so even shifts of 0.5 dex in metallicity will not change our estimated luminosity by more than the quoted 1-\sigma errors. Moreover, the change is counter-intuitive to the stellar mass-metallicity relation (i.e. higher metallicity leading to lower masses), so we do not expect that our MDF assumption is leading to significant systematic effects.

It is worth remarking that the low (few \(\times 10^5 M_\odot\)) stellar halo mass often quoted for the Milky Way is at odds with recent results from Gaia suggesting the (inner) halo is dominated by an ancient, massive accretion event with \(M^* \sim 0.5 - 1 \times 10^7 M_\odot\) (Belokurov et al. 2018; Helmi et al. 2018). Moreover, analyses of the kinematics and ages of the Galactic globular cluster populations point to a small number of massive \((\sim 10^6 M_\odot)\) Milky Way progenitors (Myeong et al. 2018; Kruisjesen et al. 2019). While it is feasible that some of the stars from these massive progenitors end up in the stellar disc (and thus avoid being accounted for in analysis given the \(|b| > 30^\circ\) cut), the majority of the debris should be
in the halo. Thus, our new estimate of \( M_{\text{halo}}^* \sim 10^9 M_\odot \) agrees with the emerging picture of a massive progenitor dominating the stellar halo mass.

5.2 Tension between stellar halo mass and metallicity?

Dwarf galaxies follow a fairly tight (\( \sim 0.2 \) dex scatter) stellar mass-metallicity relation (Kirby et al. 2013). Following the relation derived by Kirby et al. (2013) based on local group galaxies, dwarfs with masses in the range \( 0.5 - 1 \times 10^9 M_\odot \) have average metallicities of \( \langle [\text{Fe/H}] \rangle \sim -0.9 \) to \(-0.8 \) dex. The average metallicity of halo stars is \( \langle [\text{Fe/H}] \rangle \sim -1.5 \) (An et al. 2013; Zuo et al. 2017), which is seemingly at odds with a stellar halo mass of \( \sim 10^9 M_\odot \) dominated by one massive progenitor. However, this simple exercise ignores two important factors: (1) we are using the \( z = 0 \) mass-metallicity relation, and the stellar halo was built up in the past, and (2) the inner halo, within \( \sim 20 \) kpc is likely dominated by a massive progenitor, but the outer parts are likely biased towards lower mass contributors (Deason et al. 2018; Lancaster et al. 2019).

Deason et al. (2016) use cosmological N-body simulations to explore the relation between accreted stellar mass and metallicity. They used empirical stellar mass-halo mass relations, and redshift dependent stellar mass-metallicity relations, to map accreted dark matter subhaloes to stellar halo progenitors. In their Figure 7 they show that the relation between the average metallicity of the accreted stellar material and the typical destroyed dwarf mass. For progenitors of \( M^* \sim 0.5 - 1 \times 10^9 M_\odot \), the average metallicity varies between \( \langle [\text{Fe/H}] \rangle \sim -1.0 \) to \(-1.5 \). The lower metallicities are only obtained when the progenitor is destroyed at very early times, when the average metallicity of the dwarf galaxies (at fixed mass) is lower (Ma et al. 2016) (see also Fattahi et al. in preparation). Thus, in order to reconcile the stellar halo metallicity with a massive progenitor (and hence relatively massive stellar halo), this event must have occurred \( \gtrsim 10 \) Gyr ago. This is exactly the scenario that has been proposed in the \textit{Gaia}-Sausage or \textit{Gaia}-Enceladus discovery papers: an \textit{ancient}, massive accretion event (Belokurov et al. 2018; Haywood et al. 2018; Helmi et al. 2018).

Finally, as mentioned above, although the bulk of the (inner) stellar halo mass may be contributed by the \textit{Gaia}-Sausage, there is still a sprinkling of lower mass, \( \sim 10^7 - 10^8 M_\odot \) progenitors (e.g. Sgr, Sequoia), with lower average metallicities, that also contribute to the total stellar halo mass (and average metallicity). Moreover, there could also be a contribution from \textit{in-situ} halo stars to the total stellar halo mass. We discussed in Section 2 that the Galaxia + N-body models do not include \textit{in-situ} halo stars. This population, if it exists, will have similar kinematic (and chemical) properties to the thick disc. Thus, our kinematic decomposition will likely assign these \textit{in-situ} stars to the “disc” component, however, we cannot exclude the possibility that some fraction of these stars are assigned to the halo. Any contribution from \textit{in-situ} halo stars would lead to a higher stellar halo mass than expected from just one major merger event with \( M^* \sim 0.5 - 1 \times 10^9 M_\odot \).

5.3 The Milky Way in context

At fixed galaxy (or halo) mass, the stellar halo mass can vary significantly: this has been seen both in simulations and observations (e.g. Pillepich et al. 2014; Merritt et al. 2016; Elias et al. 2018; Monachesi et al. 2019). Thus, the stellar halo mass is intimately linked to the assembly history of the halo. For example, if a halo is dominated by one accretion event, then the stellar halo mass will reflect the mass of this progenitor (see e.g. Deason et al. 2016; D’Souza & Bell 2018).

In the left panel of Fig. 12 we show the ratio of stellar masses of the accreted (halo) and the galaxy (host) populations against the galaxy’s stellar mass. Here, we show the values from the \( N = 30 \) \textsc{Auriga} simulations in grey. This is a suite of high resolution cosmological hydrodynamic simulations of Milky Way mass haloes (see Grand et al. 2017 for more details). The stellar halo masses we show here only include the “accreted” stellar halo mass. As noted by Monachesi et al. (2019), the stellar halo masses in \textsc{Auriga} are significantly overestimated if we do not excise the halo stars born \textit{in-situ}. We also show observational measurements in the left panel from the Ghosts (black filled circles, Harmsen et al. 2017) and Dragonfly (pale blue filled circles, Merritt et al. 2016) surveys. Our estimate for the Milky Way is shown with the orange star symbol (assuming a Kroupa IMF). Here, we use total Galactic stellar mass derived in Licquia & Newman (2015). Even though
our stellar halo mass is larger than some previous estimates in the literature, the Milky Way stellar halo mass fraction is relatively low compared to both external galaxies and the AURIGA simulations.

In the right hand panel we use the AURIGA simulations to show $M_{\text{halo}}^*/M_{\text{gal}}^*$ against the average merger time of the destroyed dwarf galaxies that build-up the stellar halo. The points are coloured (and scaled) according to the average progenitor mass. The Milky Way are indicated with the orange star. Here, we have assumed the typical merger time for the (inner) stellar halo is 10 ± 2 Gyr ago (4 Gyr since the Big Bang). Even though most haloes in AURIGA experience more recent accretion events, it is clear that an ancient merger event, with little activity after said-event, can adequately explain the stellar halo mass fraction for the Auriga haloes. The points are coloured (and scaled) according to the average progenitor mass. The Milky Way is indicated with the orange star.

In summary, our estimate stellar halo mass supports a scenario whereby the Milky Way experienced an early (~ 10 Gyr ago), massive ($M^* = 0.5 \times 10^9 M_\odot$) merger event, and had only relatively minor mergers thereafter.\footnote{At least until the LMC is digested, see Cautun et al. (2019).}

6 CONCLUSIONS

In this work we have used counts of RGB stars from GDR2 to estimate the total stellar luminosity of the Milky Way’s halo. Using slices in colour, magnitude and position on the sky, we decompose the disc and halo RGB populations using 2-dimensional Gaussian fits to the proper motion distributions. The resulting counts of halo stars are converted into a stellar luminosity using a suite of (weighted) PARSEC isochrones. Our analysis is tested and calibrated on the Galaxia model, using the BJ05 N-body models for the stellar halo component. Our main results are summarised as follows:

- In the majority (70%) of bins in magnitude, colour and area on the sky we are able to recover the true number of halo RGB stars to ≤ 30%. Tests with the Galaxia+BJ05 models show that we are able to recover the true total luminosity to within 25%. This confidence interval takes into account realistic systematic uncertainties, such as the presence of substructure and non-Gaussian proper motion distributions.

- After applying our method to GDR2 we find a total luminosity of $L_{\text{halo}} = 8.9 \pm 2.2 \times 10^8 L_\odot$ excluding Sgr, and $L_{\text{halo}} = 10.0 \pm 2.5 \times 10^8 L_\odot$ including Sgr. The difference when Sgr is included or excluded gives a rough estimate of the total luminosity of the Sgr progenitor: $L_{\text{Sgr}} \sim 1.1 \times 10^9 L_\odot$, in good agreement with the value derived by Niederste-Ostholt et al. (2012).

- Assuming a stellar mass-to-light ratio appropriate for a Kroupa IMF ($M^*/L = 1.5$), we estimate a stellar halo mass of $M_{\text{halo}}^* = 1.5 \pm 0.4 \times 10^8 M_\odot$. This mass is larger than estimates in the literature using different stellar halo tracers (main sequence turn-off stars, blue horizontal branch stars). However, a mass of $\sim 10^7 M_\odot$ confirms the emerging picture that the (inner) stellar halo is dominated by one massive dwarf progenitor.

- We show that haloes in the AURIGA simulations that have similar stellar halo mass fractions ($M_{\text{halo}}^*/M_{\text{gal}}^* \sim 0.02$) to the Milky Way are likely formed by ancient (~ 10 Gyr) mergers. Indeed, the relatively low stellar halo mass fraction, and average metallicity of the stellar halo can only be reconciled with a massive progenitor if this was a very early merger event.

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