A New Member of the Milky Way’s Family Tree: Characterizing the Pontus Merger of Our Galaxy

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Received 2022 March 6; revised 2022 April 18; accepted 2022 April 18; published 2022 May 4

Abstract

We study the Pontus structure—a recently discovered merger that brought in ~7 globular clusters in the course of the hierarchical buildup of the Milky Way’s halo. Here, we analyze the stellar population of Pontus and examine (1) its phase-space distribution using the ESA/Gaia data set, (2) its metallicity and chemical abundances (i.e., [Fe/H], [α/Fe], [Mg/Fe], and [Al/Fe]) using the spectroscopic catalog of APOGEE DR17, and (3) the color–magnitude diagram that shows interesting features, including a possibly double horizontal branch and a small population of blue stragglers. In sum, the Pontus stars show some unique properties that suggest they likely originated from the merging of an independent satellite galaxy; however, future analysis will shed more light on the true nature of this structure. This chemodynamical analysis of Pontus stars is another step forward in our bigger quest to characterize all the merging events of our Milky Way.

Unified Astronomy Thesaurus concepts: Milky Way stellar halo (1060); Chemical abundances (224); Galaxy formation (595); Surveys (1671); Galaxy kinematics (602)

1. Introduction

The advent of the data of the Gaia mission (Gaia Collaboration et al. 2016; Lindegren et al. 2018; Gaia Collaboration et al. 2021) has allowed us to detect and characterize many substructures in the Milky Way halo (Belokurov et al. 2018; Helmi et al. 2018; Koppelman et al. 2019a; Mackereth et al. 2019; Matsuno et al. 2019; Myeong et al. 2019; Ibata et al. 2020; Naidu et al. 2020; Ramos et al. 2020; Yuan et al. 2020; Malhan et al. 2021). These substructures are remnants of those progenitor galaxies that merged with the Milky Way and contributed to the stellar (and dark matter) population of the Galactic halo. Here, our aim is to specifically analyze one of these substructures, namely Pontus, and study the dynamical and chemical properties of its stellar population.

Pontus was recently discovered by Malhan et al. (2022) as a grouping of seven globular clusters that are tightly clumped in the action–energy (J, E) space of the Milky Way. This group possesses low energy (i.e., the orbits of its components are more tightly bound to the Milky Way compared to other merger groups) and slightly retrograde motion (this is also shown in Figure 1, which we explain below). The member globular clusters include NGC 288, NGC 5286, NGC 7099/M30, NGC 6205/M13, NGC 6341/M92, NGC 6779/M56, NGC 362; there exist two additional (tentative) associations, namely NGC 6864/M75 and NGC 7089/M2. In addition to being tightly clumped in (J, E) space, these globular clusters also show a tight age–metallicity relation—again supporting the accretion scenario from a gradually enriched satellite galaxy.

While Malhan et al. (2022) could only analyze the globular cluster population of Pontus, our central objective here is to analyze its general, unbound stellar population. This is important to understand, for instance: How are the Pontus stars distributed in the phase space of the Milky Way? What are their metallicity ([Fe/H]) and chemical abundances ([X/Fe])? What can we learn about this substructure by inspecting its color–magnitude diagram (CMD)? When did the (hypothesized) Pontus galaxy merge with the Milky Way? Here, we make a first attempt to answer these questions by analyzing the Pontus stars.

This article is structured as follows. In Section 2, we first describe our procedure to construct a sample of halo stars using the Gaia data set. Next, in Section 3, we compute the orbits of these stars to specifically select the Pontus population. In Section 4, we analyze the Pontus population to examine its phase-space distribution, chemical abundances, and CMD. Finally, we discuss our findings and conclude in Section 5.

2. Selecting the Halo Stars Using Gaia

We first construct a sample of “halo” stars —those stars that possess kinematics very different from the local disk stars. For this, we use the Gaia EDR3 data set but consider only those stars that possess radial velocity measurements from the Gaia DR2 data set. This data set provides 6D phase-space information for 7,209,831 sources in heliocentric coordinates: on-sky positions (α, δ), parallaxes (ϖ), proper motions (μ_ϖ, μ_α), and line-of-sight velocities (v_los), along with their associated uncertainties. This data set also provides the G, G_{BP}, and G_{RP} magnitudes.

To select the halo population, we follow a similar prescription described by Koppelman et al. (2019b), but with a slight modification. We select those stars that follow the criteria: (1) |V − V_{LSR}| ≥ 210 km s⁻¹, where V is the velocity vector of a given star in Galactocentric Cartesian coordinates (this we obtain by transforming the heliocentric coordinates
into Cartesian coordinates using the Sun’s velocity from Drimmel & Poggio (2018) as \((V_{X,\odot}, V_{Y,\odot}, V_{Z,\odot}) = (12.9, 245.6, 7.78) \text{ km s}^{-1}\) and the Sun’s location from Gravity Collaboration et al. (2018) as \(R_\odot = 8.112 \text{ kpc}\) and \(V_{LSR}\) is the velocity vector of the local standard of rest (LSR) that we adopt from Drimmel & Poggio (2018) as \((V_{X,LSR}, V_{Y,LSR}, V_{Z,LSR}) = (1.8, 233.4, 0.53) \text{ km s}^{-1}\). (2) \(\varpi > 0\); this condition ensures that the parallaxes can be directly inverted to obtain heliocentric distances as \(D_\odot = 1/\varpi\) (this condition was implemented after correcting for the parallax zero-point of each star using the code\(^3\) provided by Lindegren et al. (2021), and henceforth all the parallaxes are zero-point corrected. (3) \(\text{parallax} \_\text{over} \_\text{error} > 5\); this quality cut ensures that our resulting sample contains well-measured parallaxes with a relative parallax error of \(<20\%\). (4) \(\text{phot} \_\text{bp} \_\text{rp} \_\text{excess} \_\text{factor} \leq 1.27\); this condition removes some of the not so well-behaved globular cluster stars, and hence, we do not apply a color-dependent correction (Arenou et al. 2018). (5) RUWE < 1.4; this value has been prescribed as a quality cut for “good” astrometric solutions by Lindegren et al. (2021). We note that the RUWE parameter was not considered by Koppelman et al. (2019b) and has also been ignored by many previous studies that had the similar objective of constructing a halo sample.

This halo selection renders 41,861 data points. In other words, \(-0.5\%\) of our Gaia sample corresponds to the halo population; at least as per our definition of halo.

3. Computing the Orbits

For the above halo stars, we compute their \(J, E\), and also other orbital parameters (e.g., apocenter, \(r_{apo}\), pericenter, \(r_{peri}\), eccentricity, \(ecc\)). This is a necessary first step to particularly select the Pontus stars using a specified range of orbital parameters; this range is described below. To compute the orbits, we adopt the Galactic potential model of McMillan (2017), which is similar to that used by Malhan et al. (2022). This is a static and axisymmetric model comprising a bulge, disk components, and a Navarro–Frenk–White halo. To set this potential model and to compute the orbital parameters, we make use of the galpy module (Bovy 2015).

Figure 1 shows the resulting \(J\) distribution (left panel) and \((J, E)\) distribution (right panel) of all the stars from our halo sample. The actions are represented in the cylindrical coordinates, i.e., \(J \equiv (J_R, J_\phi, J_z)\), where \(J_R\) corresponds to the \(Z\)-component of angular momentum (i.e., \(J_z \equiv L_z\)) and negative \(J_R\) represents prograde motion. Components \(J_\phi\) and \(J_z\) describe the extent of oscillations in cylindrical radius and \(z\) directions, respectively. In this figure, the boxes are drawn using the prescription provided by Malhan et al. (2022), and they describe the dynamical volumes occupied by different merger groups.

We particularly focus on Pontus, which corresponds to the dynamical region described by: \(E = [-1.72, -1.56] \times 10^5 \text{ km}^2 \text{ s}^{-2}\), \(J_R = [245, 725] \text{ km s}^{-1} \text{kpc}\), \(J_\phi = [-5, 470] \text{ km s}^{-1} \text{kpc}\), \(J_z = [115, 545] \text{ km s}^{-1} \text{kpc}\), \(ecc = [0.5, 0.8]\), \(r_{peri} = [1, 3] \text{kpc}\), \(r_{apo} = [8, 13] \text{kpc}\). These dynamical ranges are described using the values provided by Malhan et al. (2022), who found that the member globular clusters of Pontus lie in this range.\(^4\) This implies that Pontus stars are located in the low-energy part of the halo, and they possess slightly retrograde motion and moderately eccentric orbits. We employ these strict dynamical parameters

\(^3\) See https://gitlab.com/icc-ub/public/gaiadr3_zeropoint.

\(^4\) Because the member globular clusters of Pontus are contained within this dynamical range, it is reasonable to assume that a significant fraction of its stellar population must also be contained within this range. However, we note that the “true” extent out to which the Pontus stars are distributed in the phase space of the Milky Way could be larger.
to make a box selection that yields 1311 stars, and we refer to this sample as Pontus.5

4. Analyzing the Pontus Stars

We now analyze the Pontus stars to examine their phase-space distribution in the Milky Way (Section 4.1), their metallicity and chemical abundances (Section 4.2), and their CMD (Section 4.3).

4.1. Phase-space Distribution

Figure 2 shows the phase-space distribution of the Pontus stars.

In Figure 2, panels (a)–(c) show the spatial distribution of the Pontus stars in Galactocentric Cartesian coordinates. For comparison, we also show the stars from our halo sample. First, we note that Pontus shows far fewer stars at small Galactocentric radii, although there is no obvious signature of a spatial overdensity. This implies that the Pontus stars are almost completely phase-mixed in the galaxy. This argument is further supported by the fact that the Pontus stars occupy a very limited region in this space—very similar to the distribution of simulated substructures in Helmi & de Zeeuw (2000). The reason that the Pontus stars appear so confined in the velocity space is admittedly because of our narrow Pontus (versus halo) selection in the orbital parameter space. Second, the Pontus population is stretched along the $V_R$ direction (and also along the spherical $V_\phi$ direction, which we independently checked), implying that these stars move along radial orbits, as expected from their moderately high $J_R$ and $ecc$ values (Figure 1, left panel). Moreover, for the Pontus stars, we estimate the average and standard deviation of their $V_\phi$ distribution to be $28 \pm 25$ km s$^{-1}$, implying a retrograde structure with fairly low dispersion in $V_\phi$. Furthermore, we note that all the member globular clusters overlap with the stars in this velocity space, and this is expected because of the $J, E$ cut that we made to select the Pontus stars.

We also make a comparison of the Pontus stellar population with that of Gaia-Sausage/Enceladus (Belokurov et al. 2018; Helmi et al. 2018) because these two structures are located close to each other in ($J , E$) space, and we are interested to

5 The reason for making cuts in these seven (nonindependent) dimensions is to obtain a high-confidence (even though restricted) sample of Pontus stars. While one may argue that making cuts only in the $J$ space should be sufficient (because an orbit only has three integrals of motions), we supplement this criterion with additional orbital parameters in order to minimize the contamination. However, even this restricted selection results in a few contaminants in our Pontus sample; as we see below.

6 This is because radial velocity measurements are present for only those sources in Gaia DR2 that are brighter than $G \approx 14$ mag.

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Figure 2. Phase-space distribution of the Pontus stars (in magenta) in Galactocentric coordinates. The top panels show the spatial distribution of stars, and the bottom panels show the velocity distribution. The “star” markers correspond to the member globular clusters of Pontus. For comparison, we show the halo sample (in gray) and also the Gaia-Sausage/Enceladus stars (in blue).
examine if these two structures represent different merging events, or they simply correspond to two different fragments of the same merger? In this regard, Malhan et al. (2022) argue that Pontus and Gaia-Sausage/Enceladus are independent structures, because the member globular clusters of each group occupy different locations in $(J, E)$ space (and consequently in phase space), and they also possess a different age--metallicity relation. Here, we want to examine whether this scenario is also favored by their stellar population.

The sample of the Gaia-Sausage/Enceladus population is constructed in the same way as described for Pontus in Section 3, except using a different set of dynamical ranges as described by Malhan et al. (2022): $E \sim [-1.44, -1.16] \times 10^4$ km$^2$ s$^{-2}$, $J_R \sim [935, 2075]$ km s$^{-1}$ kpc, $J_\phi \sim [-715, 705]$ km s$^{-1}$ kpc, $J_z \sim [85, 1505]$ km s$^{-1}$ kpc, $ecc \sim [0.7, 0.9]$, $r_{pen} \sim [1, 4]$ kpc, and $r_{apo} \sim [16, 30]$ kpc. We note that this $E$ and $J_\phi$ range, which has been independently proposed by Malhan et al. (2022), is similar to that previously used by Koppelman et al. (2019a) to select and study the Gaia-Sausage/Enceladus stars. These stars are shown in panels (d)–(f) of Figure 2. As can be seen, the Gaia-Sausage/Enceladus and Pontus stars occupy very different regions in velocity space, although with small overlapping in $V_\phi$–$V_z$ space. Previous studies that made similar $J$ and $E$ selections to simultaneously analyze multiple structures have found that different structures can in fact highly overlap in the velocity space (e.g., Koppelman et al. 2019a). Furthermore, for Gaia-Sausage/Enceladus we estimate $V_\phi = -8 \pm 55$ km s$^{-1}$, suggesting that this population has almost no retrograde component and possesses a larger $V_\phi$ dispersion than Pontus.

4.2. Metallicity and Chemical Abundances

We now analyze the metallicity and chemical abundances for the Pontus stars. To this end, we cross-match our sample with the APOGEE DR17 catalog (Abdurro’uf et al. 2022) and find 88 matches. We particularly analyze the following quantities: [Fe/H], $[\alpha/Fe]$, [Mg/Fe], and [Al/Fe].

The Pontus stars are shown in Figure 3. From the [Fe/H] versus $[\alpha/Fe]$ distribution, we note that the Pontus stars clearly show an anticorrelation sequence that is indicative of their accretion (dwarf galaxy) origin. A few of the Pontus stars overlap with the disk region, suggesting that our sample contains some disk contaminants. Second, we observe a similar anticorrelation sequence in [Fe/H] versus [Mg/Fe], which is expected because Mg is an $\alpha$ element. On the other hand, a correlation sequence is observed in [Fe/H] versus [Al/Fe].

![Figure 3. Analyzing chemical abundances of Pontus stars using the APOGEE data set. Panel “a” shows the [Fe/H] vs. $[\alpha/Fe]$ distribution. The background shows 2D histograms constructed using the entire APOGEE data set (the darker the bin, the higher the number of stars in that bin). The bars at the bottom of the panel indicate the median error at that [Fe/H]. For comparison, we also show the Gaia-Sausage/Enceladus stars. Panel (b) shows the [Fe/H] vs. [Mg/Fe] distribution, and panel (c) shows the [Fe/H] vs. [Al/Fe] distribution.](image)

| Table 1: Metallicity and Chemical Abundances of the Pontus, Gaia-Sausage/Enceladus, and Halo Populations |

| Param. | Pontus | GSE | Halo |
|--------|--------|-----|------|
| [Fe/H] | $-1.403 \pm 0.047$ | $-1.274 \pm 0.03$ | $-1.185 \pm 0.009$ |
| $[\alpha/Fe]$ | ($0.368 \pm 0.035$) | ($0.253 \pm 0.021$) | ($0.497 \pm 0.007$) |
| [Mg/Fe] | $0.235 \pm 0.008$ | $0.216 \pm 0.006$ | $0.239 \pm 0.002$ |
| $[\alpha/Fe]$ | ($0.057 \pm 0.006$) | ($0.05 \pm 0.005$) | ($0.085 \pm 0.001$) |
| [Al/Fe] | $0.211 \pm 0.012$ | $0.193 \pm 0.008$ | $0.246 \pm 0.002$ |
| [Mg/Fe] | ($0.09 \pm 0.01$) | ($0.06 \pm 0.006$) | ($0.111 \pm 0.002$) |
| [Al/Fe] | $-0.228 \pm 0.014$ | $-0.237 \pm 0.009$ | $-0.037 \pm 0.005$ |
| [Mg/Fe] | ($10.03 \pm 0.111$) | ($0.074 \pm 0.007$) | ($0.285 \pm 0.004$) |

Note: From left to right, the columns provide the parameter of interest, measurements corresponding to the Pontus, Gaia-Sausage/Enceladus, and halo populations.

This distribution reveals that some of the Pontus stars overlap with the halo region, suggesting that our sample contains some halo contaminants.

For the Pontus stars, we compute the means and dispersions of their distributions in [Fe/H], $[\alpha/Fe]$, [Mg/Fe], and [Al/Fe], and these are provided in Table 1. These values are computed following our own Metropolis-Hastings–based Markov Chain Monte Carlo algorithm, based on Malhan et al. (2021), where the log-likelihood function is taken to be

$$\ln \mathcal{L} = \sum_{\text{data}} \left[-\ln \sigma_{Y_{\text{obs}}} - 0.5 \left(\frac{Y_0 - Y_d}{\sigma_{Y_{\text{obs}}}}\right)^2\right].$$

Here, $Y$ corresponds to the quantity of interest (e.g., [Fe/H] or [X/Fe]), $Y_d$ is the measured quantity, and the Gaussian dispersion $\sigma_{Y_{\text{obs}}}$ is the sum in quadrature of the intrinsic dispersion of the model together with the observational uncertainty of each data point ($\sigma_{Y_{\text{obs}}}^2 = \sigma_Y^2 + \sigma_{Y_{\text{obs}}}^2$). For this inference, we first impose conservative cuts so that our resulting subsample has reduced contamination. In doing so, we retain only those stars that possess [Fe/H] < $-0.75$ (to reduce disk contaminants), $[\alpha/Fe] > 0$, and [Al/Fe] < 0 (to reduce halo contaminants). This selection renders 60 stars, and this subsample is used to compute the values provided in Table 1. Table 1 quotes the mean and the standard deviation corresponding to the posterior PDFs of different quantities.

For comparison, we also show the Gaia-Sausage/Enceladus stars in Figure 3. These stars appear to follow similar sequences.
to the average metallicity of Pontus. Panel match our Pontus sample with the LAMOST DR5 data set A similar KS test has also been previously used to examine chemical Figure 4.

The Astrophysical Journal Letters, 930: L9 (7pp), 2022 May 1

In particular, the Pontus stars on average are slightly more metal poor than the Gaia-Sausage In particular, the Pontus stars on average are slightly more metal poor than the Gaia-Sausage

Fe shows the measurements for our halo sample. These measure-

Table 2

Results Corresponding to the Two-sample Kolmogorov–Smirnov (KS) Test Performed on Pontus and Halo Populations, Gaia-Sausage/Enceladus, and Halo Populations, and Pontus and Gaia-Sausage/Enceladus Populations

| Param       | Pontus-Halo | GSE-Halo | Pontus-GSE |
|-------------|-------------|----------|------------|
| [Fe/H]      | <0.001(>5σ) | <0.001(>5σ) | 0.028(>2.0σ) |
| [α/Fe]      | <0.001(>5σ) | <0.001(>5σ) | 0.414(>0.5σ) |
| [Mg/Fe]     | <0.001(>5σ) | <0.001(>7σ) | 0.254(>0.5σ) |
| [Al/Fe]     | <0.001(>6σ) | <0.001(>8σ) | 0.358(>0.5σ) |

Note. The leftmost column provides the name of the parameter. The next three columns give p-values of the KS test (and the corresponding significance at which the null hypothesis can be rejected).

The CMD of the Pontus stars. Panel (a) shows Pontus stars in magenta and the halo population in gray. We also plot a stellar population model that is similar to the average metallicity of Pontus. Panel (b) is similar to panel (a), except Pontus stars are now colored by their [Fe/H] values. To make this plot, we also cross-match our Pontus sample with the LAMOST DR5 data set (Zhao et al. 2012; Xiang et al. 2019).

Table 2 summarizes the result from the Kolmogorov–Smirnov (KS) test that we perform to compare the [Fe/H], [α/Fe], [Mg/Fe], and [Al/Fe] distributions of Pontus and Gaia-Sausage/Enceladus, Pontus and halo, and Gaia-Sausage/Enceladus and halo. The KS test is performed for the null hypothesis that the two given samples are drawn from the same distribution. For instance, a value of >5σ in Table 2 implies that the null hypothesis can be rejected at the >5σ level. This comparison shows (1) the [Fe/H], [α/Fe], [Mg/Fe], and [Al/Fe] distributions of both Pontus and Gaia-Sausage/Enceladus are very different from those of the halo population. (2) For the Pontus and Gaia-Sausage/Enceladus populations, their distributions in [α/Fe], [Mg/Fe], and [Al/Fe] are quite similar (as the null hypothesis can only be rejected at the >0.5σ level). (3) The null hypothesis—that the two [Fe/H] samples for Pontus and Gaia-Sausage/Enceladus are drawn from the same distribution—can be rejected at the >2σ level.

4.3. Stellar Population

Figure 4(a) shows the CMD of the Pontus population. To construct this figure, we first correct Gaia magnitudes for dust extinction using Schlegel et al. (1998) maps and assuming the extinction ratios $A_G/A_V = 0.86117$, $A_{RP}/A_V = 1.06126$, and $A_{BP}/A_V = 0.64753$ (as listed on the web interface of the PARSEC isochrones; Bressan et al. 2012). Henceforth, all magnitudes and colors refer to these extinction-corrected values. Next, we transform these corrected apparent magnitudes ($G_{BP,0}$, $G_{RP,0}$, $G_0$) into absolute magnitudes ($M_{G_{BP,0}}$, $M_{G_{RP,0}}$, $M_G$) using heliocentric distances of stars ($D_*$). For comparison, we also show the CMD of the halo population.
From Figure 4(a), we first notice that the Pontus population contains more intrinsically brighter stars than fainter stars, and this is likely due to our quality cuts that can give rise to such asymmetries (e.g., Koppelman et al. 2019b). The broadness of the Pontus CMD indicates that these stars do not resemble a single stellar population but rather favor a wide [Fe/H] distribution (as we also found in Section 4.2) and possibly also a wide age distribution. The mean of this age distribution is likely \( \sim 12 \) Gyr—this point is illustrated by plotting an isochrone model corresponding to \([(\text{Fe}/\text{H}), \text{Age}] = (-1.3 \text{ d}x 12 \text{ Gyr})\) that fits the CMD reasonably well.

The CMD of Pontus shows some interesting features. For instance, Figure 4(a) shows the possibility of two horizontal branches and a small population of blue stragglers. In order to examine whether these features are really representative of the Pontus population, or they are the Milky Way interlopers, we inspect Figure 4(b), which shows the CMD colored by the [Fe/H] measurements. As can be seen, we do not possess a substantial number of [Fe/H] measurements for the horizontal branch stars, and therefore, we cannot confidently confirm the presence of a double horizontal branch. However, a few of these stars do possess [Fe/H] measurements that are consistent with the average [Fe/H] of Pontus. On the other hand, for the blue stragglers, we possess an [Fe/H] measurement for only one star, and it is slightly more metal rich than the average [Fe/H] of Pontus.

5. Conclusion and Discussion

We have performed the chemodynamical analysis of the stellar population of the recently discovered Pontus structure. For this, we used the Gaia data set to analyze its phase-space distribution and further used the APOGEE data set to examine its metallicity and chemical abundances.

In regard to the dynamical properties: the Pontus stars possess low energy and slightly retrograde motion (see Figure 1(b)), and they move on moderately eccentric orbits. This implies that the (hypothized) progenitor galaxy would have merged on a radial, and slightly retrograde, orbit. This argument is also supported by the fact that the Pontus stars are stretched in the velocity space along the radial direction (see Figure 2).

In regard to the metallicity and chemical abundances: The Pontus population is metal poor and \( \alpha \) enhanced (see Table 1), which is indicative of its accretion (dwarf galaxy) origin. Based on this, we argue that Pontus likely merged with the Milky Way \( >5–6 \) Gyr ago. This can be argued using the observations of the Sagittarius merger (Ibata et al. 1994). For Sagittarius, we know that its stars possess \([\text{Mg}/\text{Fe}] = -0.03\) (Hayes et al. 2020) and that this merging occurred \( \sim 5–6 \) Gyr ago (Ruiz-Lara et al. 2020). Given that Pontus is more Mg enhanced than Sagittarius, this tentatively suggests that the Pontus galaxy must have accreted earlier than Sagittarius, and therefore, it did not get sufficient time to get enriched in Fe (via Type Ia supernovae) and ended up retaining more of Mg (and also other \( \alpha \) elements). This early accretion scenario for Pontus is also supported by its very low energy, implying that the progenitor galaxy was likely accreted very early on when the Milky Way was much smaller in size (than today), and therefore, any merging galaxy would have ended up populating the very inner (low-energy) regions of the galaxy. Moreover, given the [Fe/H] of Pontus, it appears that the progenitor galaxy must have been a massive system (with \( M_\odot \sim 10^7 M_\odot \); this value is obtained using Kirby et al. 2013 relation).

The CMD of the Pontus stars shows some interesting features (Figure 4). These include a possibly double horizontal branch and a small population of blue stragglers. We note that a similar twin horizontal branch feature has also been observed in the globular cluster NGC 6205/M 13 (Grundahl et al. 1998), which is associated with the Pontus galaxy (Malhan et al. 2022). However, we note that Grundahl et al. (1998) discuss the \(~0.4 \text{ mag} \) “overluminous” horizontal branch for only blue stars in M13, and here we observe a gap of \(~1 \text{ mag} \) between the two branches. In Pontus, if the brighter branch is a real feature, it may correspond to the post-horizontal branch stars (e.g., Sandquist et al. 2010; Davis et al. 2022).

During our analysis, we also made comparisons between the stellar populations of Pontus and Gaia-Sausage/Enceladus. This was done because these two groups are located close to each other in the \((J_\odot, E)\) space, and we were interested to examine whether they represent different merging events or two fragments of the same merger.

It is interesting to note both the differences and similarities between Pontus and Gaia-Sausage/Enceladus structures. First, Figure 1 shows that while these two structures are located close to each other in the \((J_\odot, E)\) space, their difference in this dynamical space is still larger compared to the difference between other structures that are also located close to each other (e.g., Sagittarius–Cetus or Cetus–LMS-1/Wukong or Arjuna–Sequoia–L’itoi). Nonetheless, it is not unexpected for the stellar debris of a single massive merger to span a large range of distribution in \( L_\odot–E \) space (e.g., Helmi et al. 2018). However, this last point is difficult to confirm because the true dynamical boundaries for Gaia-Sausage/Enceladus and Pontus are currently unknown (in terms of observations). Second, for Gaia-Sausage/Enceladus, we deem that our orbit selection criteria (that is based on Malhan et al. 2022) do not necessarily underestimate the dynamical extent of this structure, as previous studies have also used a similar range of \( L_\odot–E \) to select and study the Gaia-Sausage/Enceladus population (e.g., Koppelman et al. 2019a). Moreover, we find that these two populations show different behavior in the velocity space (Figure 2), although this is a consequence of our orbit selection criteria. Furthermore, while these two populations possess similar \([\alpha/\text{Fe}], [\text{Mg}/\text{Fe}], \text{ and } [\text{Al}/\text{Fe}], \text{ distributions, they somewhat differ in their [Fe/H] distributions (see Tables 1 and 2). Also, as shown in Malhan et al. (2022), the member globular clusters of Pontus and Gaia-Sausage/Enceladus possess slightly different age–metallicity relations. For future analyses of Pontus, it will be useful to run detailed \( N \)-body simulations to better understand how this merging event would have taken place and to predict the present-day phase-space distribution of its stars in the Milky Way. Moreover, building a chemical evolution model for Pontus will be crucial to constrain its star formation history and the ages of its stars (e.g., Vincenzo et al. 2019). These constraints, together, will also be useful to confirm more confidently whether Pontus is the low-energy (low \( J_\odot \)) fragment of Gaia-Sausage/Enceladus or that they truly are the remnants of independent merging events. Furthermore, this will also shed light on the similar or distinct origins of Pontus and Thamnos (Koppelman et al. 2019a), which is another structure that lies close to Pontus in the \((J_\odot, E)\) space. These future steps should be easy to explore with the
upcoming Gaia DR3 RVS data set (which will be 2 mag deeper than DR2 RVS) and the spectroscopic data sets of the WEAVE (Dalton et al. 2014) and 4MOST (de Jong et al. 2019) surveys that will enable us to gather high-quality phase-space and chemical abundance information for a larger sample of Pontus stars. Therefore, future analysis of Pontus, and its comparison with the other mergers, will allow us to gain a more comprehensive understanding of the formation of the Milky Way’s vast stellar halo.

We thank our referee for reviewing this manuscript. It is a pleasure to thank Hans-Walter Rix, Morgan Fouesneau, Jianhui Lian, and Anke Arensten for their help and suggestions. K.M. acknowledges support from the Alexander von Humboldt Foundation at Max-Planck-Institut für Astronomie, Heidelberg, and is also grateful to the IAU’s Gruber Foundation Fellowship Programme for their financial support.

This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement.

Funding for SDSS-III has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, and the US Department of Energy Office of Science. The SDSS-III website is http://www.sdss3.org/.

SDSS-III is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS-III Collaboration including the University of Arizona, the Brazilian Participation Group, Brookhaven National Laboratory, Carnegie Mellon University, University of Florida, the French Participation Group, the German Participation Group, Harvard University, the Instituto de Astrofisica de Canarias, the Michigan State/Notre Dame/JINA Participation Group, Johns Hopkins University, Lawrence Berkeley National Laboratory, Max Planck Institute for Astrophysics, Max Planck Institute for Extraterrestrial Physics, New Mexico State University, New York University, Ohio State University, Pennsylvania State University, University of Portsmouth, Princeton University, the Spanish Participation Group, University of Tokyo, University of Utah, Vanderbilt University, University of Virginia, University of Washington, and Yale University.

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