High-precision chemical abundances of Galactic building blocks. II.
Revisiting the chemical distinctness of the Helmi streams

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ABSTRACT

Context. The Helmi streams are a kinematic substructure whose progenitor is likely a dwarf galaxy. Although 20 years have passed since their discovery, it is still uncertain whether their members are chemically distinguishable from other halo stars in the Milky Way.  

Aims. We aim to precisely characterize the chemical properties of the Helmi streams.  

Methods. We analyzed high-resolution, high signal-to-noise ratio spectra for 11 Helmi stream stars through a line-by-line abundance analysis. We compared the derived abundances to homogenized literature abundances of the other halo stars, including those belonging to other kinematic substructures, such as Gaia-Enceladus and Sequoia.  

Results. Compared to typical halo stars, the Helmi stream members clearly show low values of [X/Fe] in elements produced by massive stars, such as Na and α-elements. This tendency is seen down to metallicities of at least [Fe/H] ≈ −2.2, suggesting type Ia supernovae already started to contribute to the chemical evolution at this metallicity. We find that the [α/Fe] ratio does not evolve significantly with metallicity, making the Helmi stream stars less distinguishable from Gaia-Enceladus stars at [Fe/H] ≳ −1.5. The almost constant but low value of [α/Fe] might be indicative of quiescent star formation with low efficiency at the beginning and bursty star formation at later times. We also find extremely low values of [Y/Fe] at low metallicity, providing further support for the claim that light neutron-capture elements are deficient in Helmi streams. While Zn is deficient at low metallicity, it shows a large spread at high metallicity. The origin of the extremely low Y abundances and Zn variations remains unclear.  

Conclusions. The Helmi stream stars are distinguishable from the majority of the halo stars if homogeneously derived abundances are compared.

1. Introduction

The Helmi streams were discovered by Helmi et al. (1999) as a kinematic substructure among halo stars, which is an expected signature of past galaxy accretion. They were thus one of the first pieces of evidence for the hierarchical formation of the Milky Way expected from the standard cosmology. The streams were discovered as an overdensity in the plane of angular momenta in a sample of < 100 low-metallicity stars. Later studies also confirmed their existence (Chiba & Beers 2000; Kepley et al. 2007; Myeong et al. 2018; Koppelman et al. 2018). Their progenitor was likely a dwarf galaxy with a stellar mass of ~ 10^8 M⊙ and a mean metallicity of [Fe/H] ~ −1.5 that was accreted to the Milky Way around 5 ~ 8 Gyr ago (Kepley et al. 2007; Koppelman et al. 2019).

Even though the streams were discovered more than 20 years ago, their chemical properties have not received much attention until recently. Roederer et al. (2010) studied the chemical abundances of 12 stars in the stream, concluding that the stars have similar abundance ratios as the rest of the halo stars. In recent years, Limberg et al. (2021), Gull et al. (2021), Aguado et al. (2021), and Nissen et al. (2021) conducted chemical analysis for the Helmi stream members. While Gull et al. (2021) reach the same conclusion as Roederer et al. (2010), the other studies hint at possible chemical peculiarities of the streams. For example, the Sr abundance seems to be much lower than typical for halo stars at [Fe/H] ≲ −2 (Aguado et al. 2021); two stars in a binary system in the Helmi streams, namely G112-43 and G112-44, have enhanced ratios of [Mn/Fe], [Ni/Fe], [Cu/Fe], and [Zn/Fe] compared to other accreted stars in the Milky Way (Nissen et al. 2021); and the [α/Fe] ratio seems to be decreasing at [Fe/H] ≳ −2 (Limberg et al. 2021)(Aguado et al. 2021).

Many of the previous comparisons made use of heterogeneous literature compilation. They were therefore limited by systematic uncertainties, which can be as large as 0.4 dex in [Fe/H] and 0.2 dex in [X/Fe]. This can easily obscure or falsely create abundance peculiarities, as we will see later in this paper. Another complication arises because the literature sample was often a mixture of accreted and in situ stars. As Nissen & Schuster (2010 hereafter, NS10) showed from their homogeneously analyzed samples, the Milky Way halo contains two major populations, accreted and in situ stars, which differ in abundance ratios. Without understanding the origin of the comparison sample, it remains unclear if the chemical peculiarities of the Helmi stream stars, if any, indicate simply that they are accreted or that the progenitor had a unique evolution. Nissen et al. (2021) is the only
We obtained new high-resolution spectra for all objects except LP894-3. The signal-to-noise ratios are converted to per 0 Å.

Table 1. Summary of the data

| Object | Gaia EDR3 source id | S/N_{4500 Å} | S/N_{5531 Å} | S/N_{6370 Å} |
|--------|-------------------|---------------|---------------|---------------|
| 2447_5952 | 2447968154259005952 | 80 | 108 | 173 |
| 4998_5552 | 499874180535413552 | 72 | 83 | 78 |
| 6170_9904 | 6170808423037019904 | 87 | 88 | 77 |
| 6615_9776 | 661566106517269776 | 97 | 161 | 122 |
| 6914_3008 | 6914409197757803008 | 73 | 86 | 120 |
| J1306+4154 | 1527475951701753984 | 50 | 65 | 53 |
| J1436+0929 | 1176187720407158912 | 134 | 110 | 91 |
| J1553+3909 | 1376687518318241536 | 84 | 73 | 55 |
| J1730+5309 | 141677522385396160 | 84 | 63 | 42 |
| J1642+2041 | 4564066449004092298 | 63 | 60 | 86 |
| LP894-3 | 2891152566675457280 | 97 | 150 | 143 |

Notes. We obtained new high-resolution spectra for all objects except LP894-3. The signal-to-noise ratios are converted to per 0 Å.

Table 2. Property of the targets

| Object | π (mas) | σ(π) (mas) | G (mag) | B_P - R_P (mag) | E(B - V) (mag) | RV (km s^{-1}) |
|--------|---------|------------|--------|-----------------|---------------|----------------|
| 2447_5952 | 2.817 | 0.021 | 11.963 | 0.677 | 0.096 | 145.5 |
| 4998_5552 | 3.463 | 0.018 | 12.561 | 0.784 | 0.000^a | -187.6 |
| 6170_9904 | 3.743 | 0.018 | 10.573 | 0.728 | 0.064 | -122.4 |
| 6615_9776 | 4.984 | 0.014 | 12.064 | 0.768 | 0.010 | -276.9 |
| 6914_3008 | 3.195 | 0.017 | 12.622 | 0.720 | 0.015 | 113.9 |
| J1306+4154 | 1.470 | 0.013 | 13.499 | 0.668 | 0.046 | -294.7 |
| J1436+0929 | 3.294 | 0.019 | 12.172 | 0.671 | 0.006 | -301.4 |
| J1553+3909 | 1.944 | 0.013 | 13.619 | 0.741 | 0.018 | -288.3 |
| J1642+2041 | 0.997 | 0.013 | 13.497 | 0.765 | 0.070 | -246.3 |
| J1730+5309 | 0.751 | 0.011 | 13.967 | 0.817 | 0.006 | -301.4 |
| LP894-3 | 5.347 | 0.038 | 11.090 | 0.710 | 0.010 | 303.0^b |

Notes. ^a) This object is not covered by Green et al. (2019). Since Schlegel et al. (1998) provide E(B - V) = 0.01 and since this object is nearby, we assumed E(B - V) = 0.0 for this object. ^b) From Ishigaki et al. (2012).

exception in the sense that they compared Helmi stream members with accreted stars using homogeneously derived chemical abundance. However, larger samples could aid our understanding of the interesting abundance pattern reported in the two stars in a binary system.

Throughout this study, we aim to precisely characterize the chemical abundances of the Helmi stream stars and to compare them with homogeneously derived abundances of other components in the Milky Way halo, including Gaia-Enceladus, in situ stars (NS10; Reggiani et al. 2017, hereafter R17), and Sequoia (Matsumo et al. 2022, hereafter, Paper I). The precise chemical abundance ratios tell us about the progenitor's properties, but the chemical distinctness of kinematic substructures, if found, would also enable us to “chemically tag” stars originating from the same progenitor. In Paper I, we show that a combination of a line-by-line analysis for a carefully selected sample and homogenization of literature abundances using standard stars is a powerful way to precisely characterize the chemical properties of kinematic substructures.

We studied the chemical abundance of the Helmi stream stars in the same way as in Paper I. Namely, we analyzed high signal-to-noise ratio spectra for 11 stars in the Helmi streams, measured their chemical abundance through a line-by-line analysis with careful treatment of uncertainty, and compared them with other halo stars in NS10 and R17 after homogenizing all the abundances. We describe the observation, data reduction, targets, and stars in the literature in Section 2. In Section 3, after briefly explaining our approach for the chemical abundance measurement and homogenization, we present chemical abundance ratios of the Helmi stream stars. After providing discussions in Section 4, we summarize our findings in Section 5.

2. Data

2.1. Observation

We obtained high-resolution spectra for ten stars with the High Dispersion Spectrograph (Noguchi et al. 2002) on the Subaru telescope1. The selection and properties of the targets are described in the following subsection. The observations were conducted on August 9-10, 2020, with the standard setup of the HDS (StdYd), which yields a wavelength coverage from \( \sim 4000 \) Å to \( \sim 6800 \) Å. We used the image slicer #2 (Tajitsu et al. 2012), which provides a resolving power of \( R \sim 80,000 \). The data reduction was performed using an IRAF script3, including CCD linearity correction, scattered light subtraction, aperture correction, and final spectra analysis.
2.2. Targets

Targets were selected based on the orbital angular momenta of the stars following Koppelman et al. (2019). Namely, the selection criteria were that the angular momentum along the z-axis of the Milky Way ($L_z$) and $L_{\text{perp}}$, which is given by $\sqrt{L_x^2 + L_y^2}$, must satisfy the conditions $|L_z| < 5$ kpc km s$^{-1}$ and $L_{\text{perp}} < 1500$ kpc km s$^{-1}$. We also restricted our sample to those stars around the turn-off region using Gaia DR2 photometry. The exact selection criteria were $G_{\text{BP}} < 1000$ and $1750 < L_{\text{perp}}/\text{kpc km s}^{-1} < 1500$ (the kinematic selection) and $0.5 < G_{\text{RP}} < 4.5$ and $G_{\text{abs}} < 5.8$ (the color-magnitude selection), where $G_{\text{BP}}$, $G_{\text{RP}}$, and $G_{\text{abs}}$ are Gaia $BP$, $RP$, and $BP$ magnitude, and the absolute magnitude in the Gaia $G$ band, respectively.

Initially, for the target selection, we used Gaia DR2 astrometry, photometry, and radial velocity (Gaia Collaboration et al. 2018), and Large Sky Area Multi-Object Fiber Spectroscopic Survey data. We also searched archives for high signal-to-noise ratio and high-resolution spectra for stars that satisfy our selection criteria described in the following subsection. We find that LP894-3 satisfies our selection and has spectra in the Subaru telescope archive. We, therefore, analyzed the archival spectrum of this star. The spectrum used is the same as that used by Ishigaki et al. (2012).

Notes. \(^{a}\) Subclass defined by Dodd et al. (2022). In the last column, “hiL” indicates a clump with a higher $L_{\text{perp}}$ and “loL” one with a lower $L_{\text{perp}}$. 

Table 3. Kinematics of the targets

| Object            | $v_z$ (km s$^{-1}$) | $\sigma(v_z)$ (km s$^{-1}$) | $L_z$ (kpc km s$^{-1}$) | $\sigma(L_z)$ (kpc km s$^{-1}$) | $L_{\text{perp}}$ (kpc km s$^{-1}$) | $\sigma(L_{\text{perp}})$ (kpc km s$^{-1}$) | $E/10^5$ (km s$^{-2}$) | $\sigma(E)/10^5$ (km s$^{-2}$) | subclass \(^{a}\) |
|-------------------|---------------------|----------------------------|-------------------------|--------------------------------|-------------------------------|---------------------------------|-----------------------------|-------------------------------|-------------------|
| 2447_5952         | -216.7              | 1.1                        | 1278                    | 11                             | 1872                          | 9                              | -1.022                      | 0.007                         | ...               |
| 4998_5552         | 230.1               | 1.1                        | 1020                    | 6                              | 1846                          | 9                              | -1.429                      | 0.002                         | ...               |
| 6170_9904         | -272.8              | 1.3                        | 1200                    | 9                              | 2201                          | 11                             | -1.342                      | 0.003                         | hiL               |
| 6615_9776         | 213.8               | 0.9                        | 1345                    | 2                              | 1757                          | 8                              | -1.339                      | 0.003                         | loL               |
| 6914_3008         | -283.9              | 1.5                        | 1437                    | 8                              | 2279                          | 12                             | -1.275                      | 0.004                         | hiL               |
| J1306+4154        | 281.3               | 0.9                        | 1288                    | 2                              | 2363                          | 7                              | -1.293                      | 0.002                         | hiL               |
| J1436+0929        | -249.4              | 0.9                        | 1226                    | 4                              | 2050                          | 7                              | -1.312                      | 0.003                         | hiL               |
| J1553+3909        | -268.6              | 0.8                        | 1304                    | 6                              | 2208                          | 7                              | -1.299                      | 0.002                         | hiL               |
| J1642+2041        | -217.0              | 1.2                        | 1339                    | 7                              | 1737                          | 9                              | -1.392                      | 0.003                         | loL               |
| J1730+5309        | 238.3               | 2.4                        | 1423                    | 14                             | 1965                          | 19                             | -1.384                      | 0.004                         | loL               |
| LP894-3           | -219.8              | 0.7                        | 1015                    | 6                              | 1813                          | 6                              | -1.283                      | 0.003                         | ...               |

Fig. 1. Distribution of stars in kinematic spaces, namely $E = L_z$, $L_{\text{perp}}$, and $v_z$. The insets in the left two panels show better distribution of the stars that are part of the Helmi streams. The Helmi stream selection from Koppelman et al. (2019) is shown as a dashed box in the inset of the middle panel. Stars are hatched according to the subgroups found by Dodd et al. (2022). Three stars (2447_5952, 4998_5552, and LP894-3) are not associated with either of the subgroups. An open symbol is assigned only to 2447_5952 since it has much larger energy than the other Helmi stream stars. We used filled symbols for stars from NS10 and R17 if they satisfy the kinematic selection for Gaia-Enceladus (see Paper I).
The Na abundances in the comparison literature are in LTE (NS10) and in non-LTE (R17). This inconsistency does not affect our conclusions since we put all the abundances onto the same scale and since NS10 used Na lines that require small non-LTE corrections (< 0.1 dex).

3. Chemical abundances

3.1. Abundance analysis

We provide here a brief description of our analysis, and readers can refer to Paper I for a complete and detailed explanation. The abundance measurements were based on equivalent width measurements, where we assumed a Voigt profile for the line shape. We applied spectral synthesis for Si, Mn, Zn, and Y. Hyperfine structure splitting was considered for Na, Mn, and Ba. Abundances were estimated based on the assumption of local thermodynamic equilibrium (LTE) using MOOG (Sneden 1973) and based on one-dimensional plane-parallel MARCS atmosphere models (Gustafsson et al. 2008). We applied non-LTE corrections of Lind et al. (2011) to the obtained Na abundance through the INSPECT database.4

The effective temperature \( T_{\text{eff}} \) was determined by minimizing the correlation between the excitation potentials and line-by-line abundances of neutral iron lines. The microturbulent velocity \( \xi \) was determined similarly by minimizing the correlation between reduced equivalent widths and abundances. The surface gravity \( \log g \) was determined from temperature, luminosity, and stellar mass, where the luminosity was obtained by applying a bolometric correction of Casagrande & VandenBerg (2018) to the absolute magnitude in the Gaia G band, and mass was derived from isochrone fitting in the color-magnitude diagram. This method of \( \log g \) determination has an advantage over the spectroscopic method, requiring the ionization equilibrium between Fe I and Fe II, in that it does not strongly depend on the assumed \( T_{\text{eff}} \). For the stellar parameter determination, we used the simple mean of iron abundances derived from individual Fe II lines because Fe II abundances are less affected by the non-LTE effect and temperature uncertainty than Fe I abundances. We took correlated uncertainties into consideration for the estimates of uncertainties. The derived parameters are presented in Table 4.

The elemental abundances are the weighted average of the abundances derived from the individual lines. The weights were determined following the prescription by Ji et al. (2020). The weights on individual lines as well as line-by-line abundances and their sensitivities to stellar parameters are summarized in Table 5 When considering [X/Fe], we used the Fe abundance from the same ionization stage as the species X.

4 Data obtained from the INSPECT database, version 1.0 (www.inspect-stars.com).

The Na abundance in the comparison literature are in LTE (NS10) and in non-LTE (R17). This inconsistency does not affect our conclusions since we put all the abundances onto the same scale and since NS10 used Na lines that require small non-LTE corrections (< 0.1 dex).
Table 4. Stellar parameters

| Object   | $T_{\text{eff}}$ (K) | $\sigma(T_{\text{eff}})$ (K) | $\log g$ (dex) | $\sigma(\log g)$ (dex) | $v_t$ (km s$^{-1}$) | $\sigma(v_t)$ (km s$^{-1}$) | $\Delta [\text{Fe/H}]$ (dex) | $\sigma(\Delta [\text{Fe/H}])$ (dex) | $\rho_{T_{\text{eff}}, \log g}$ | $\rho_{T_{\text{eff}}, v_t}$ | $\rho_{\Delta [\text{Fe/H}], \rho_{T_{\text{eff}}, \log g}}$ | $\rho_{\log g, \Delta [\text{Fe/H}]}$ | $\rho_{v_t, \Delta [\text{Fe/H}]}$ |
|----------|----------------------|------------------------------|----------------|------------------------|---------------------|-----------------------------|---------------------------------|----------------------------------|-------------------------------|------------------|--------------------------------------------|-------------------------------|------------------|
| 2447_5952 | 6275                 | 84                           | 4.195          | 0.040                  | 1.371              | 0.101                       | -1.416                          | 0.028                            | 0.498                         | 0.547                         | 0.263                        | 0.058                        | 0.613                        | -0.337             |
| 4998_5552 | 5562                 | 57                           | 4.413          | 0.058                  | 1.022              | 0.154                       | -1.282                          | 0.040                            | 0.071                         | 0.695                         | -0.305                       | -0.268                       | 0.605                        | -0.579             |
| 6170_9904 | 5946                 | 72                           | 3.789          | 0.043                  | 1.251              | 0.102                       | -1.706                          | 0.033                            | 0.425                         | 0.605                         | 0.003                        | 0.138                        | 0.389                        | -0.395             |
| 6615_9776 | 5490                 | 61                           | 4.481          | 0.033                  | 0.752              | 0.226                       | -2.175                          | 0.026                            | 0.440                         | 0.836                         | -0.540                       | 0.239                        | 0.195                        | -0.782             |
| 6914_3008 | 5706                 | 69                           | 4.400          | 0.034                  | 0.821              | 0.157                       | -1.730                          | 0.025                            | 0.399                         | 0.836                         | -0.343                       | 0.128                        | 0.323                        | -0.500             |
| J1306+4154| 6175                 | 108                          | 4.261          | 0.051                  | 1.272              | 0.114                       | -1.211                          | 0.029                            | 0.479                         | 0.696                         | 0.094                        | 0.180                        | 0.583                        | -0.221             |
| J1436+929 | 6109                 | 55                           | 4.374          | 0.031                  | 1.370              | 0.104                       | -1.839                          | 0.038                            | 0.428                         | 0.634                         | 0.012                        | 0.166                        | 0.249                        | -0.244             |
| J1553+3909| 5623                 | 60                           | 4.346          | 0.036                  | 0.871              | 0.184                       | -1.409                          | 0.022                            | 0.405                         | 0.745                         | -0.526                       | 0.175                        | 0.339                        | -0.749             |
| J1642+2041| 5840                 | 70                           | 3.784          | 0.089                  | 1.293              | 0.083                       | -1.275                          | 0.043                            | -0.037                        | 0.762                         | -0.143                       | -0.446                       | 0.827                        | -0.501             |
| J1730+5309| 5778                 | 59                           | 3.706          | 0.071                  | 1.245              | 0.067                       | -1.661                          | 0.039                            | -0.024                        | 0.587                         | -0.021                       | -0.541                       | 0.776                        | -0.502             |
| LP894-3  | 6035                 | 83                           | 4.341          | 0.038                  | 1.321              | 0.142                       | -1.505                          | 0.034                            | 0.561                         | 0.856                         | 0.154                        | 0.387                        | 0.370                        | 0.021              |
Table 5. Linelist and line-by-line abundance

| Object species | \( \lambda \) (Å) | \( \chi \) (eV) | log \( g \) (dex) | \( EW \) (mÅ) | \( \sigma(EW) \) (mÅ) | A(\( X \)) (dex) |
|----------------|------------------|----------------|----------------|--------------|----------------|------------------|
| NaI 5682.633   | 2.102            | -0.706        | 5.1            | 0.5          | 4.675          |
| NaI 5889.959   | 0.000            | -0.193        | 172.0          | 8.0          | 4.558          |
| NaI 5895.910   | 0.000            | -0.575        | 151.6          | 7.0          | 4.505          |
| MgI 4167.271   | 4.346            | -2.379        | 5.3            | 0.6          | 6.472          |
| MgI 4730.040   | 4.340            | -0.193        | 172.0          | 8.0          | 4.558          |
| MgI 5895.910   | 0.000            | -0.575        | 151.6          | 7.0          | 4.505          |
| MgI 4167.271   | 4.346            | -2.379        | 5.3            | 0.6          | 6.472          |

Notes. The full table is available online at the CDSr; only a portion of the table is shown here.

![Graphs showing [Na/Fe] and [Mg/Fe] abundance ratios of the Helmi stream stars (red symbols). Also plotted are halo stars from NS10 and R17, with Gaia-Enceladus stars shown with filled symbols. G112-43 and G112-44 from NS10 are shown with red stars since their kinematics are consistent with the Helmi streams. We also show kinematically selected Sequoia stars from Paper I.](image)

![Graphs showing [Na/Fe] and [Mg/Fe] abundance ratios of the Helmi stream stars (red symbols). Also plotted are halo stars from NS10 and R17, with Gaia-Enceladus stars shown with filled symbols. G112-43 and G112-44 from NS10 are shown with red stars since their kinematics are consistent with the Helmi streams. We also show kinematically selected Sequoia stars from Paper I.](image)

All of the analysis was conducted relative to HD59392, for which we adopted \( T_{\text{eff}} = 6012 \) K, \( \log g = 3.954 \), \( v_r = 1.4 \) km s\(^{-1}\), and [Fe/H] = -1.6 (NS10; Paper I). The elemental abundance of this star was taken from NS10 and Nissen & Schuster (2011). In Paper I, we validated our results using a few standard stars and confirm that our abundances are on the same scale as NS10, Nissen & Schuster (2011) and [Fe/H] = +0.4 and the other has a solar [\( \alpha/Fe \)]. Assuming the chemical composition of HD59392, we first computed equivalent widths of absorption lines using the standard \( \alpha \)-enhanced model atmosphere. We then derived abundances with the other model from the computed equivalent widths. The maximum difference between the assumed and derived abundances is found.

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in strong lines to be $\sim 0.02$ dex. Since the variation in [$\alpha$/Fe] among our sample is $\sim 0.2$ dex and since every line is affected in the same direction, the effect of different [$\alpha$/Fe] in model atmospheres is at most 0.01 dex when discussing [X/H] and even smaller when discussing [X/Fe].

### 3.2. Results

Figure 3 shows [Na/Fe] and [Mg/Fe] ratios of the Helmi stream stars together with the halo stars from NS10 and R17 and the Sequoia stars from Paper I, all of which are on the same abundance scale. We note that we indicate Gaia-Enceladus stars in the literature with filled symbols in figures. At $-1.8 \leq [\text{Fe/H}] \leq -1.6$, the Helmi stream stars show similar Na and Mg abundances to Sequoia stars, having clearly lower [Na/Fe] and [Mg/Fe] values compared to other halo stars including Gaia-Enceladus stars. The Helmi stream stars with [Fe/H] $\geq -1.5$ also have lower values in these abundance ratios than in situ halo stars. Although they are less separated from Gaia-Enceladus stars at this high metallicity, they still tend to show lower [Mg/Fe] values compared to Gaia-Enceladus stars. The most metal-poor star 6615_9776 also seems to show a lower abundance of Na and Mg compared to other halo stars. We, however, note that this star is in the metallicity range, [Fe/H] $< -2.1$, where R17 measured the abundance of stars using a standard star that is different from what they used for stars with [Fe/H] $> -2.1$. Hence, there is no guarantee that the abundance of 6615_9776 and R17 stars with similar metallicity are on the same scale. Readers can refer to Paper I for the effect of different standard stars (see the results of abundance comparison for HIP28104 in Section 3 of Paper I).

Figure 4 shows Si, Ca, and Ti abundances, which are also known to be different between stars with different origins (NS10; Paper I). The behavior of the Helmi stream stars in Ca and Ti is similar to that in Na and Mg; the stars show clearly lower abundance at low metallicity than most halo stars, while they become more indistinguishable from Gaia-Enceladus stars at higher metallicity. For Si, the picture is unclear because the Si lines become too weak at [Fe/H] $\leq -1.5$.

The observed trends in the $\alpha$-elements confirm the results of Limberg et al. (2021) and Aguado et al. (2021) in the sense that the Helmi stream stars have lower $\alpha$-element abundance compared to general Milky Way stars. We added here another important result; the $\alpha$-element abundances of the Helmi stream stars are even lower than another accreted population, the Gaia-Enceladus stars, especially at [Fe/H] $\leq -1.5$. Moreover, contrary to the conclusion of Limberg et al. (2021) and Aguado et al. (2021) that the [$\alpha$/Fe] ratios decrease with metallicity, the evolution in $\alpha$-elements (Mg, Ca, and Ti) with metallicity observed in the present study is rather flat from [Fe/H] $\sim -2.1$ to [Fe/H] $\sim -1.2$. The low $\alpha$ abundance of the Helmi stream stars is also in contrast with Roederer et al. (2010), who concluded that the Helmi stream stars have a similar abundance as other halo stars. We consider that our precise and homogeneous abundance comparisons enable us to detect the abundance difference between the Helmi stream stars and Gaia-Enceladus stars and precisely depict the chemical evolutionary track followed by the Helmi streams. We further discuss the importance of the homogeneous abundance analysis in Section 4.2.

The abundances of elements near the iron-peak, namely Cr, Mn, Ni, and Zn, are shown in Figure 5. It has been reported that Cr, Ni and Zn abundances are different between accreted stars and in situ stars (Nissen & Schuster 2011). We, therefore, expect that these abundances are different among the various kinematic substructures with different $\alpha$-element abundances. We, however, do not see apparent abundance differences between the Helmi stream stars and the other halo stars in Cr and Ni at our measurement uncertainty. On the other hand, Zn appears depleted in the Helmi streams at low metallicity, while there is a large variation at high metallicity. The Helmi stream stars tend to show a low value of [Mn/Fe] at [Fe/H] $\leq -1.5$ while they seem to be consistent with typical Gaia-Enceladus stars at higher metallicity.

The high Zn abundance of G112-43 and G112-44 was reported in Nissen & Schuster (2011) and confirmed in Nissen et al. (2021). It is also supported for G112-43 by our analysis in Paper I as described in Section 3.1. The other Helmi stream stars in the present study, on the other hand, do not show a similar Zn enhancement. We attempt to interpret the Zn abundance evolution of the Helmi streams in Section 4.1.

Abundances of neutron-capture elements are shown in Figure 6. The Helmi stream stars are clearly deficient in Y at low metallicity. This behavior of Y resembles that of Sr reported by Aguado et al. (2021), which is expected since both are light neutron-capture elements and since these two elements usually show similar trends with [Fe/H]. It is hard to conclude if the Ba abundance evolution of the Helmi streams is distinct from that of Gaia-Enceladus or other halo stars because of large scatter. However, we remark that the Helmi stream stars tend to be on the lower side in [Ba/Fe] at given [Fe/H] compared to other halo stars.

As described in Section 2.2 symbols in Figures 3 to 6 are hatched according to the subgroups discussed by Dodd et al. (2022). Both subgroups show similar abundance peculiarities compared to other halo stars (lower abundances of $\alpha$-elements and Y). This result supports that both subgroups can be regarded as a part of the Helmi streams. We made a similar inspection between stars with positive and negative $\nu$, and reached the same conclusion.

We note that the only star with an exceptionally high value of $E_\nu$ (2447.5952) has a slightly different elemental abundance than the other Helmi stream stars. The different behavior of this star is especially prominent in Ca, Ti and neutron-capture elements (Figures 4 and 6). This might indicate that the Helmi streams do not extend toward high $E_\nu$, which is consistent with the recent identification of Helmi stream members based on clustering analysis of halo stars (Lövdal et al. 2022; Ruiz-Lara et al. 2022).

### 4. Discussion

#### 4.1. Properties of the Helmi stream progenitor

The chemical properties of the Helmi streams can be summarized as follows. The abundances of elements usually produced by explosions of massive stars (e.g., Na and $\alpha$-elements) are generally lower than most of the other halo stars, including Gaia-Enceladus stars. While the difference to Gaia-Enceladus stars becomes less clear at [Fe/H] $\geq -1.5$, the Helmi stream stars still tend to be on the lower side of the distribution in [Mg/Fe], [Ca/Fe], and [Ti/Fe]. Zn and Y also show similar trends as these elements, suggesting they originate in massive stars. This chemical abundance pattern is similar to that seen for Sequoia stars (Paper I).

The low abundance of $\alpha$-elements and Na are usually attributed to Fe enrichments from type Ia supernovae (SNe Ia). Interestingly, SNe Ia seem to have started to operate in the Helmi stream progenitor already at very low metallicity ([Fe/H] $< -2.2$) since even the lowest-metallicity star in the sample...
(6615_9776) has low abundances of $\alpha$-elements and Na. Assuming that every system has the same abundance ratios among Na, $\alpha$-elements, and Fe before the onset of SNe Ia, we can tentatively provide an upper limit for the “knee” metallicity as $[\text{Fe/H}]_{\text{knee}} \leq -2.4$ from the ~ 0.2 dex lower $[\text{Mg/Fe}]$ of 6615_9776 than the halo stars from R17.

Another interesting feature in $\alpha$-elements is that there is no apparent decreasing trend in $[\alpha/\text{Fe}]$ with metallicity. Moreover, a few stars at $[\text{Fe/H}] \sim -1.2$ seem to have higher $[\alpha/\text{Fe}]$ than the stars at $[\text{Fe/H}] \sim -1.8$, although it remains to be seen if they are actually the Helmi stream members rather than contaminants from heated thick disk or other accreted populations. If this almost flat or slightly increasing trend is confirmed with a larger sample of homogeneous abundances, it would resemble the observed trend in the Large Magellanic Could (LMC) by Nidever et al. (2020). These authors suggest that such a chemical evolution trend cannot be reproduced in models with a constant star formation efficiency. They suggest that such a trend needs a starburst at a late phase. Although the progenitor of the Helmi streams might have experienced a similar starburst at a late phase, the old age of the majority of the Helmi stream stars (Koppelman et al. 2019; Ruiz-Lara et al. 2022) suggests that the

![Graphs showing $[\text{Si/Fe}]$, $[\text{Ca/Fe}]$, and $[\text{Ti/Fe}]$ against $[\text{Fe/H}]$ for Helmi stream stars.](image-url)

**Fig. 4.** $\alpha$-element abundances of the Helmi stream stars. The symbols follow those of Figure 3. When a star does not have any detectable lines for an element, we indicate the abundances corresponding to the 1-$\sigma$ and 3-$\sigma$ upper limits on the equivalent widths, respectively shown with the location of the symbols and the upper end of the error bars.
transition from quiescent to bursty star formation occurred on a shorter timescale than that in LMC. A future chemodynamical study with precise stellar age as well as chemical evolution modeling would be necessary to confirm this scenario.

The Y abundance of the Helmi stream stars is particularly low at $[\text{Fe/H}] < -1.8$. Together with the results of Aguado et al. (2021) on Sr abundance, this suggests that the Helmi stream stars have very low abundances of light neutron-capture elements. Such a low light neutron-capture element abundance is not common among the Milky Way stars but is seen in low-mass dwarf galaxies such as Draco and Ursa Minor dwarf spheroids and most of the ultra-faint dwarf galaxies (e.g., Frebel & Norris 2015).

Several nucleosynthesis processes have been proposed as production sites of these light neutron-capture elements, including $r$-process in neutron star mergers (Wanajo et al. 2014, Watson et al. 2019), in magneto-rotational supernovae (Winteler et al. 2012), or in collapsars (Siegel et al. 2019), $s$-process in low- to intermediate-mass stars (Karakas & Lattanzio 2014), weak $s$-process in rapidly rotating massive stars (Frischknecht et al. 2012; Choplin et al. 2018), and weak $r$-process in electron-capture supernovae (Wanajo et al. 2011). It is not yet clear which process is the dominant source of the elements in the early Universe (see discussions by, e.g., Côté et al. 2019; Prantzos et al. 2018; Kobayashi et al. 2020). Since we here discuss the low-metallicity end of the sample, the production of neutron-capture
elements would not be dominated by low- to intermediate-mass stars (e.g., de los Reyes et al. 2022). One possible explanation for the low light neutron-capture element abundances of the Helmi streams is that, as a result of the low stellar mass of the galaxy, the progenitor did not experience rare r-process nucleosynthesis events, such as neutron star mergers, electron capture supernovae, and magneto-rotational supernovae. In this case, a small amount of light neutron-capture elements could be produced by rapidly rotating massive stars (Hirai et al. 2019; Tarumi et al. 2021). Another explanation is that the progenitor dwarf galaxy had a small number of rotating massive stars. The small number of rotating massive stars might be a result of the top-light initial mass function in dwarf galaxies (Weidner & Kroupa 2005), or different distribution of initial rotation velocity of stars. The observational indication by Gull et al. (2021) that metal-poor stars of the Helmi streams show r-process abundance pattern in neutron-capture elements heavier than Ba might favor the second possibility. However, it is necessary to investigate the abundance pattern of light neutron-capture elements in order to understand the cause of the low light neutron-capture element abundance of the Helmi streams. A larger sample of low-metallicity Helmi stream stars with neutron-capture element abundances would also be welcomed. They would enable us to constrain the property of the nucleosynthesis processes, such as their event rates, by studying how neutron-capture elements were enriched as a function of metallicity (e.g., Tsujimoto et al. 2017).

The [Zn/Fe] values observed at high metallicity are also noteworthy. While the binary pair G112-43 and G112-44 have high Zn abundance (Nissen et al. 2021), other Helmi stream stars do not share such a high abundance, resulting in a large star-to-star variation in [Zn/Fe]. Although Nissen et al. (2021) noted that the binary pair is also enhanced in Mn, Ni, and Cu, the measurement uncertainties in the present study are not high enough to see if there are significant scatters in Mn and Ni abundances among the Helmi stream stars. A significant dispersion in [Zn/Fe] at high metallicity is also reported in the Sculptor dwarf spheroidal galaxy (Skuladottir et al. 2017). While Hirai et al. (2018) provided a theoretical calculation of Zn enrichments in dwarf galaxies, assuming electron capture supernovae as one of the sources of Zn, they find it challenging to produce a large scatter at high metallicity. Based on iron-group element abundances, Nissen et al. (2021) suggest pure helium detonation type Ia supernovae could be a promising nucleosynthesis event producing the unique abundance pattern of the binary pair. It remains to be seen whether chemical evolution models including this type of SNe Ia can explain the Zn abundance variation within a galaxy. A larger sample of stars with precise multi-element abundances would be helpful to establish, for example, if the binary pair is a chemical outlier or a tail of [Zn/Fe] distribution in the system and if the Zn abundance correlates with abundances of other elements.

4.2. Helmi streams in the literature

In this section, we highlight the importance of homogeneous chemical abundance through a comparison of our results with those presented in the literature, by Roederer et al. (2010), by Limberg et al. (2021), by Gull et al. (2021), and by Aguado et al. (2021). All but Limberg et al. (2021) compared the chemical abundance of the Helmi stream stars with a literature compilation without homogenizing the chemical abundances.

6 We consider five stars observed with high-resolution spectrographs (HORuS and UVES) for the Aguado et al. (2021) sample.
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This study

2.5
2.0
1.5
1.0
0.5

[Fe/H]
1.0
0.5
0.0
0.5
1.0

[Na/Fe]
[Ca/Fe]
[Ti/Fe]
[Zn/Fe]
[Y/Fe]

Fig. 7. Chemical abundance of the Helmi stream stars from literature, namely Roederer et al. (R10; 2010), Aguado et al. (A21; 2021), and Gull et al. (G21; 2021). We also include Helmi stream stars in the present study and in NS10. The background gray points are from the SAGA database (Suda et al. 2008, 2011; Yamada et al. 2013). The UVES spectra of three stars from Aguado et al. (2021) were reanalyzed and abundances from the reanalysis are included in the figure. Abundances from our reanalysis and those from Aguado et al. (2021) are connected with a solid line for each star.

Figure 7 compares the abundances of the Helmi stream stars from those literature studies and from our present work, with those of stars in the Milky Way from various literature sources (SAGA database: Suda et al. 2008, 2011; Yamada et al. 2013). To confirm the membership to the Helmi streams, we recomputed angular momenta of the stars in Roederer et al. (2010), Gull et al. (2021), and Aguado et al. (2021) consistently and reselected the Helmi stream members. As there is no report of radial velocity in Aguado et al. (2021), we adopted radial velocity measurements by SDSS or LAMOST for their stars. For the stars in common between Roederer et al. (2010) and Gull et al. (2021), we prioritized the measurements by the latter study over the former. We also included in the figure abundances that we obtained for three stars studied by Aguado et al. (2021) by reanalyzing their UVES spectra. For this reanalysis, we reetermined stellar parameters following the same procedure as described in Paper I and estimated the abundances using these parameters.

We first emphasize the importance of homogeneity in abundance by using the three stars from Aguado et al. (2021) that we reanalyzed. As can be seen in Figure 7, stars from Aguado et al. (2021) seem to have higher $\alpha$-elements abundances compared to the Helmi stream stars in the present study if we adopt the reported abundances. On the other hand, our reanalysis shows that the three stars actually have similar abundances as the sample in the present study, although the uncertainties are larger due to different spectral quality. To investigate the effect of different stellar parameters, we fixed $T_{\text{eff}}$ and $\log g$ to the values adopted by Aguado et al. (2021), determined $v_t$ and metallicity, and then measured abundances instead of redetermining the four stellar parameters. The results do not change significantly compared to what we obtained from the full reanalysis. The source of difference thus could be due to different atomic data, line selection, and/or spectral synthesis software.

The different abundance from Aguado et al. (2021) and our reanalysis is not too surprising since it has been known that systematic uncertainty can be significant when abundances from different studies are compared without homogenization. For example, G112-43 is a well studied star and its abundance is available in a number of literature (Ryan et al. 2001; Charbonnel & Primas 2005; Zhang et al. 2009; Ishigaki et al. 2010; Nis-
pair G112-43 and G112-44 are the only stars with clear Zn enhancements, and all the other Helmi stream stars at [Fe/H] \geq -1.5 have Zn abundances comparable to or lower than Gaia-Enceladus stars. It would be interesting to investigate the detailed [Zn/Fe] distribution with a lager number of stars.

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Appendix A: Additional table
Table A.1. Abundances of the Helmi stream stars

| Element | Helmi 2447 & 5952 | Helmi 6170 & 9904 |
|---------|------------------|------------------|
| N/X | $\sigma_{N/X}$ | N/X | $\sigma_{N/X}$ |
| FeI | 103 | -1.399 | 0.032 | 88 | -1.378 | 0.042 |
| N/X | $\sigma_{N/X}$ | N/X | $\sigma_{N/X}$ |
| FeII | 12 | -1.420 | 0.025 | 5 | -1.315 | 0.029 |
| MgI | 7 | -1.078 | 0.034 | 3 | -1.010 | 0.033 |
| CaI | 19 | -1.010 | 0.044 | 18 | -1.051 | 0.040 |
| SiI | 2 | -1.051 | 0.038 | 6 | -1.007 | 0.038 |
| CaII | 18 | -1.100 | 0.044 | 17 | -1.140 | 0.044 |
| TiI | 11 | -1.059 | 0.038 | 15 | -1.100 | 0.038 |
| TiII | 13 | -1.060 | 0.038 | 8 | -1.100 | 0.038 |
| CrI | 4 | -1.030 | 0.038 | 2 | -1.080 | 0.038 |
| MnI | 5 | -1.030 | 0.038 | 7 | -1.120 | 0.038 |
| NiI | 14 | -1.010 | 0.038 | 22 | -1.090 | 0.038 |
| ZnI | 2 | -1.010 | 0.038 | 2 | -1.090 | 0.038 |
| YII | 2 | -1.010 | 0.038 | 2 | -1.090 | 0.038 |
| BaII | 4 | -1.010 | 0.038 | 4 | -1.090 | 0.038 |

$\sigma_{N/X}$ and $\sigma_{N/X}$ denote the uncertainties in the abundances.
Table A.1. continued.

| Element | J1730+5309 | LP894-3 |
|---------|-------------|---------|
|        | N  | [X/H]  | σ  | [X/Fe] | σ  | N  | [X/H]  | σ  | [X/Fe] | σ  |
| ZnI     | 2  | -1.912 | 0.045 | -0.084 | 0.044 | 2  | -1.333 | 0.041 | 0.128  | 0.046 | 2  | -1.436 | 0.042 | -0.160 | 0.042 |
| YII     | 0  | <-2.531(-2.238) | <-0.709(-0.416) | 2  | -1.711 | 0.042 | -0.301 | 0.046 | 2  | -1.601 | 0.056 | -0.352 | 0.051 |
| BaII    | 3  | -2.332 | 0.052 | -0.510 | 0.061 | 4  | -1.783 | 0.043 | -0.373 | 0.044 | 4  | -1.609 | 0.057 | -0.360 | 0.050 |

Notes. For upper limits, we provide both 1-σ and 3-σ upper limits. The values in parenthesis are for the 3-σ upper limits.