The Chemical Nature of the Young 120-Myr-old Nearby Pisces–Eridanus Stellar Stream Flowing through the Galactic Disk

Keith Hawkins\textsuperscript{1*}, Madeline Lucey\textsuperscript{1}, and Jason Curtis\textsuperscript{2}

\textsuperscript{1}Department of Astronomy, The University of Texas at Austin, 2515 Speedway Boulevard, Austin, TX 78712, USA
\textsuperscript{2}Department of Astrophysics, American Museum of Natural History, Central Park West, New York, NY, USA

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

Recently, a new cylindrical-shaped stream of stars up to 700 pc long was discovered hiding in the Galactic disk using kinematic data enabled by the Gaia mission. This curious stream of stars, dubbed the Psc–Eri stream, was initially thought to be as old as 1 Gyr, yet its stars shared a rotation period distribution consistent with the 120-Myr-old Pleiades cluster. In this work, we explore the detailed chemical nature of this stellar stream. We carried out high-resolution spectroscopic follow-up of 42 Psc–Eri stream stars using McDonald Observatory, and combined these data with information for 40 members observed with the low-resolution LAMOST spectroscopic survey. Together, these data enabled us to measure the abundance distribution of light/odd-Z (Li, Na, Al, Sc, V), \(\alpha\) (Mg, Si, Ca, Ti), Fe-peak (Cr, Mn, Fe, Co, Ni, Zn), and neutron capture (Sr, Y, Zr, Ba, La, Nd, Eu) elements across the Psc–Eri stream. We find that the stream is (1) near solar metallicity with [Fe/H] = –0.03 dex and (2) has a metallicity spread of 0.07 dex (0.04 dex when outliers are excluded). We also find that (3) the abundance of Li indicates that Psc–Eri is \(\sim\) 120 Myr old, consistent with the gyrochronology result. We find that (4) the stream has a \([X/Fe]\) abundance spreads of \(0.06 < \sigma[X/Fe] < 0.20\) dex in most elements, and (5) no significant abundance gradients across its major axis except a potentially weak gradient in [Si/Fe]. These results together show that the Psc–Eri stream is a uniquely close, young, chemically interesting laboratory for testing our understanding of star and planet formation.

Key words: Galaxy: abundances – stars: abundances – stars: kinematics and dynamics

1 INTRODUCTION

Stellar clusters and associations provide crucial environments for exploring the formation and early evolution of stars and planets. The advent of large astrometric surveys, such as the Gaia mission (Gaia Collaboration et al. 2018), and spectroscopic surveys, such as the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST, Cui et al. 2012; Luo et al. 2015) survey, among others, have enabled the discovery of new stellar clusters and associations (e.g. Kounkel & Covey 2019).

Meingast et al. (2019) discovered a 400-pc-long stellar stream in the Galactic disk with the 6D position and velocity data from the second data release from the Gaia mission. Referred to as Pisces–Eridanus (Psc–Eri) by Curtis et al. (2019), this stellar stream provides an important new source of young stars to study star formation and test theories of chemical and dynamical evolution of stellar systems. This is especially true given its proximity (\(d \approx 80-226\) pc with a median distance of 129 pc) and population size. Initially \(\sim 250\) members of the stream were discovered in the stream (Meingast et al. 2019). However, more recent studies, which used the initial 250 members as a starting point, have used a variety of techniques and uncovered upwards of \(\sim 2000\) members (e.g. Curtis et al. 2019b; Ratzénbäck et al. 2020; Röser & Schilbach 2020). For example, the recent census by Röser & Schilbach (2020) identified 1387 members distributed across 700 pc.

Meingast et al. (2019) noted that this newly discovered cigar-shaped stream was built up from a mass of \(\sim 2000\) M\(_\odot\). The tightness of the main sequence shown in the color–magnitude diagram (CMD) of this system indicates that it...
is a single coeval stellar population. The identification of the evolved star 42 Ceti as a member indicated that it was consistent with being ~1 Gyr old. Using 27 stars in common with the low resolution LAMOST spectroscopic survey, these authors found that the metallicity of the stream was [Fe/H] = −0.04 ± 0.15 dex, consistent with a disk-like population. The results outlined in their work was interesting because it is rare to find a 1-Gyr-old star cluster close to the Sun (e.g. Dias et al. 2002; Kharchenko et al. 2005). This made the Psc–Eri stream uniquely interesting as it would be one of the oldest structures in a 200 pc volume from the Sun. In fact, based on shape and age of Psc–Eri stream, Meingast et al. (2019) concluded that that it could be a descendant of a tidally disrupting cluster or OB association. They further suggested that this structure can be thought of as a counterpart of the stellar streams that have been discovered in the stellar halo.

Using data from NASA’s Transiting Exoplanet Survey Satellite (TESS), Curtis et al. (2019a) found that the rotation period distribution of 101 Psc–Eri stream stars precisely overlapped with that of the Pleiades cluster, demonstrating that it is a coeval system with an age of ≈120 Myr, much younger than the 1 Gyr age suggested by Meingast et al. (2019). Curtis et al. (2019a) also identified 34 high-mass stars as candidate members, which supports the young 120 Myr age. Furthermore, the 3D velocity dispersion (1.3 km s$^{-1}$, though this value is limited by the Gaia DR2 RV errors), is on the order of other known OB associations (Tuc–Hor: 1.1 km s$^{-1}$; Kraus et al. 2014). However, whether this system is analogous to an evolved OB association, disintegrating cluster, or a resonant structure is still yet to be shown.

Recently, Ratzenböck et al. (2020) uncovered as many as ~2000 Psc–Eri stream stars and used them to infer the properties of the stream. They found that the it is ~110 Myr old and has a metallicity of Z = 0.016 (i.e., [Fe/H] = −0.10 dex). They also noted that the total mass of the stream is closer to 770 M$_\odot$.

2 DATA

2.1 High-Resolution Spectroscopic follow-up

In order to investigate the detailed chemical nature of the stream, we carried out high-resolution spectroscopic follow-up of 42 Psc–Eri stream stars identified in Table A.1 of Meingast et al. (2019). Briefly, these authors identified probable candidates in the Psc–Eri stream by first selecting a high-quality kinematic subsample of stars from the second data release of the Gaia mission (Gaia DR2, see their Section 2). They then preformed a wavelet decomposition and searched for substructure using the DBSCAN clustering algorithm. While they found previously known structures, they also reported the discovery of a prominent previously unknown structure that Curtis et al. (2019a) refers to as the Psc–Eri stream. We selected 42 of the 258 probable Psc–Eri stream stars identified from these authors that were observable during mid 2019. The observational properties of the observed stars can be found in Table 1. In addition to observing 42 stream candidates, we also observed the twilight sky in order to obtain a solar spectrum. The solar spectrum will be used to quantify the level systematics of our atmospheric abundance measurements with respect to the literature (e.g. Asplund et al. 2005).

The spectroscopic follow up was completed using the Tul Echelle Spectrograph (Tull et al. 1995) on the 2.7m Harlan J. Smith Telescope at McDonald Observatory in mid 2019. The instrument was set up using the slit #4 mode, which enabled us to obtain optical spectra with a resolving power of R = λ/Δλ ~ 60000. The spectra have a wavelength coverage of ~3800–9000 Å, with increasing inter-order gaps as one moves towards the red part of the spectrum. The spectra were reduced and extracted using the standard procedures (e.g. subtraction of the bias, dividing by the flat field, optimal spectra extraction and scattered light subtraction) using the echelle package within the IRAF suite of software.

In order to ensure that we can measure high-quality stellar parameters and abundances, we obtained high signal-to-noise ratio (SNR) data, with SNR > 50 pixel$^{-1}$ for all targets, including the solar spectrum. The approximate SNR for each star can be found in column 13 in Table 1.

Once the spectra were reduced and extracted, an initial continuum normalization was done, order-by-order assuming a fifth order spline. Once each order was flattened they were stitched using the `scombine task` within IRAF. Radial velocities (RVs) were determined by cross correlation with a solar spectral template with the iSpec package (Blanco-Cuaresma et al. 2014). The RVs measured can be found in Table 1. Fig. 1 illustrates that the measured RVs from our high-resolution follow-up as a function of those derived from Gaia. This enabled us to confirm the Gaia RVs with an offset of 0.78 km s$^{-1}$ and a dispersion of 0.82 km s$^{-1}$ across the 42 stars observed. With the reduced, extracted, wavelength- and RV-corrected data in hand, in Section 3, we describe how we used these spectra to measure the at-
and its uncertainty, along with our measured RVs and its uncertainty from the high-resolution spectra obtained in this work are listed to study the chemo-dynamical nature of the Milky Way's...
The LAMOST survey has obtained low-resolution (R~1800) optical (3700 < λ < 9000 Å) spectra for 8 million stars spread across the Milky Way. This is one of the largest collections of optical spectra of stars to date, and hence has the largest number of overlap with the Psc–Eri stream. The LAMOST catalog contains not only stellar classifications but also RV information in addition to basic stellar parameters (T\textsubscript{eff}, log g, and [Fe/H]) for upwards of 5 million stars using the LAMOST stellar parameter pipeline (Luo et al. 2015).

Most recently, Xiang et al. (2019) supplemented these stellar parameters with the derivation of 16 atmospheric abundances, [X/Fe], for 6 Million Stars apart of the fifth data release of the LAMOST survey. They derived these abundances via label transfer (through a neural net framework) using data from the GALAH and APOGEE surveys as a training set. To get the most out of the LAMOST data, we have cross matched this value-added stellar parameter and abundance catalog against the stream candidates. Unlike in Meingast et al. (2019), who found 27 stars in the stream that were also observed with the third data release of LAMOST, we found 40 stars observed with LAMOST DR5 that are also apart of the stream. In order to best combine our high-resolution abundance results with LAMOST, we observed 13 stars in the stream that were also observed in LAMOST (see the last column of Table 1 for more details). This is important specifically because it allows us to quantify the level of systematics between our abundances relative to those derived in Xiang et al. (2019) with the LAMOST spectra. Once correcting for these systematics, we can combine our results with LAMOST to explore the detailed chemical nature of this newly discovered stream in a more comprehensive way.

3 STELLAR PARAMETER AND ABUNDANCE ANALYSIS

The primary effort of this work is to measure the chemical nature of the Psc–Eri stellar stream in the Galactic disk. In order to do that, we must first measure the stellar atmospheric parameters, including the effective temperature (T\textsubscript{eff}), surface gravity (log g), metallicity ([Fe/H]) and microturbulent velocity (ξ) from the observed stellar spectra (see Section 2). To accomplish this, we used the Brussels Automatic Code for Characterizing high acCuracy Spectra (BACCHUS; Masseron et al. 2016) code. BACCHUS requires the use of both a line list of atomic and molecular information as well as stellar atmosphere models. Similar to Hawkins et al. (2020), we take the atomic line list from the fifth version of the Gaia-ESO linelist (Heiter et al., submitted). Hyperfine structure splitting is included for Sc i, V i Mn i, Co i, Cu i, Ba ii, Eu ii, La ii, Pr ii, Nd ii, Sm ii (Heiter et al., submitted). Molecular information for the following species were also included: CH (Masseron et al. 2014), and CN, NH, OH, MgH and C\textsubscript{2} (T. Masseron, private communication). SiH molecules are adopted from the Kurucz linelists\(^3\) and those from TiO, ZrO, FeH, CaH from B. Plez (private communication) are also included. BACCHUS also uses the MARCS model atmosphere grid (Gustafsson et al. 2008), along with TURBOSPECTRUM (Alvarez & Plez 1998; Plez 2012) in order to synthesize spectra.

For a detailed discussion on how BACCHUS is used to derive the stellar parameters and atmospheric abundances, we refer the reader to Section 3 of Hawkins et al. (2020). We use the same setup, input physics (e.g., line list, model atmospheres, and line selection) as that work. Briefly, BACCHUS determines the stellar parameters using the Fe excitation-ionization balance technique. Under this technique, one tunes the T\textsubscript{eff}, log g, and ξ of the model atmosphere in order to ensure that there is no correlations between the derived Fe abundance and the excitation potential and reduced equivalent width of the ~100 lines used. In addition, the Fe i and Fe ii abundances are required to match.

Once the stellar parameters were determined, the individual abundances for 22 elements were derived. These elements span different families including the light/odd-Z (Li, Na, Al, Sc, V), α (Mg, Si, Ca, Ti), Fe-peak (Cr, Mn, Fe, Co, Ni, Zn), and neutron capture (Sr, Y, Zr, Ba, La, Nd, Eu). The reported elements were determined via \(\chi^2\) minimization between a set of synthetic and observed spectra using the ‘abund’ module within BACCHUS. This module starts by fixing the stellar parameters to the values derived above, then proceeds to recompute synthetic spectra for a given

\(^3\) http://kurucz.harvard.edu/linelists/linemol/
set of elemental lines differing the $[X/Fe]^4$, between $-0.6 < [X/Fe] < +0.6$ and determine a best fit value by $\chi^2$ minimization. If the value of $[X/Fe]$ is outside of this range BACCHUS will automatically adjust the range higher or lower and refit the spectra. The reported elemental abundance ratio is the median $[X/Fe]$ value for all quality unflagged lines$^5$. The reported uncertainty in $[X/Fe]$ is estimated as the standard error in the mean for all lines used in the abundance determination. When only one absorption line is useable, we conservatively assume the uncertainty is 0.10 dex. We note that this is likely an underestimate of the total internal uncertainty as it does not propagate the uncertainty of the stellar parameters ($T_{\text{eff}}, \log g, \xi$) to the chemical abundances. For these types of stars, it is expected this will be on the order of 0.05–0.10 dex depending on the element (e.g. Hawkins et al. 2020).

4 RESULTS

4.1 Stellar Parameters and Metallicity Distribution of the Psc–Eri Stream

Before we determined the stellar parameters ($T_{\text{eff}}, \log g, [Fe/H]$, and $\xi$) for all stars in our Psc–Eri stream sample, we started with deriving these parameters for our twilight spectrum of the Sun. This first test allows us to ensure that the method, selected Fe lines, and input physics (e.g., the atomic and molecular line list and model atmosphere grid) are appropriate. We report our derived Solar atmospheric parameters and detailed abundances in Table 2 using the observed twilight spectrum. In addition, we also tabulate reference values for the solar parameters and abundances taken from Asplund et al. (2005). As shown in Table 2, we find the following Solar atmospheric parameters: $T_{\text{eff}} = 5707 \pm 25$ K, $\log g = 4.45 \pm 0.15$, $[Fe/H] = 0.00 \pm 0.07$, and $\xi = 0.88 \pm 0.05$ km s$^{-1}$. These values are encouragingly similar to the reference values of $T_{\text{eff}} = 5777$ K, $\log g = 4.44$, $[Fe/H] = 0.00 \pm 0.07$, and $\xi = 1.20 \pm 0.50$ km s$^{-1}$ (e.g., Jofré et al. 2014). We also derived the absolute Solar atmospheric abundances$^6$ for the elements studied here. The Solar abundances differ from the literature by as much 0.30 dex. In order to maintain internal consistency, we choose to use our derived solar abundances as the reference point for all $[X/Fe]$ ratios instead of assuming them from the literature (e.g. Asplund et al. 2005).

The atmospheric stellar parameters ($T_{\text{eff}}, \log g, [Fe/H]$, and $\xi$) for all stars in our sample can be found in Table 3.

$^4$ Chemical abundances are represented in the standard way as a logarithmic ratio of element X to element Y, relative to the Sun, $[X/Y]$, such that $[X/Y] = \log \left( \frac{N_X}{N_Y} \right)_{\odot} - \log \left( \frac{N_X}{N_Y} \right)_{\text{star}}$, where $N_X$ and $N_Y$ are the number of element X and element Y per unit volume respectively. We also note that instead of assuming the solar abundances from literature (e.g. Asplund et al. 2005), we derive them directly from our Twilight spectrum.

$^5$ BACCHUS has a decision tree algorithm which flags low-quality lines that are saturated, have too low signal-to-noise ratios, or are suspiciously high (or low). For more details the reader should consult Hawkins et al. (2015) and Masseron et al. (2016).

$^6$ We note that the absolute abundances of species X, denoted as $\log A_X$, are in the usual form where $\log A_X = \log \left( \frac{N_X}{N_H} \right)_{\text{star}} - \log \left( \frac{N_X}{N_H} \right)_{\odot}$ where $\log N_H$ is normalized to 12.00.
Table 2. Solar Atmospheric Parameters and Chemical Abundances

| Parameter | Value | σ Value | Lines Used | Ref Value$^a$ | σ Ref Value$^a$ |
|-----------|-------|---------|------------|---------------|----------------|
| $T_{\text{eff}}$ (K) | 5707 | 25 | ... | 5777 | 3 |
| log g | 4.45 | 0.15 | 23 | 4.437 | ... |
| $\xi$ | 0.00 | 0.07 | 109 | 0.00 | 0.05 |
| Na | 6.19 | 0.03 | 9 | 6.17 | 0.04 |
| Mg | 7.38 | 0.03 | 5 | 7.53 | 0.09 |
| Al | 6.38 | 0.10 | 1 | 6.37 | 0.06 |
| Si | 7.50 | 0.04 | 13 | 7.51 | 0.04 |
| Ca | 6.32 | 0.02 | 21 | 6.31 | 0.04 |
| Ti | 4.80 | 0.01 | 49 | 4.90 | 0.06 |
| V | 3.82 | 0.02 | 24 | 4.00 | 0.02 |
| Sc | 3.16 | 0.05 | 11 | 3.05 | 0.08 |
| Cr | 5.54 | 0.02 | 20 | 5.64 | 0.10 |
| Mn | 5.24 | 0.03 | 12 | 5.39 | 0.03 |
| Co | 4.77 | 0.04 | 17 | 4.92 | 0.08 |
| Ni | 6.19 | 0.04 | 22 | 6.23 | 0.04 |
| Cu | 4.00 | 0.06 | 50 | 4.21 | 0.04 |
| Zn | 4.47 | 0.07 | 2 | 4.60 | 0.03 |
| Cr | 5.54 | 0.02 | 20 | 5.64 | 0.10 |
| Sr | 2.74 | 0.14 | 2 | 2.92 | 0.05 |
| Y | 1.97 | 0.05 | 9 | 2.21 | 0.02 |
| Zr | 2.71 | 0.05 | 6 | 2.59 | 0.04 |
| Ba | 2.23 | 0.06 | 5 | 2.17 | 0.07 |
| La | 1.18 | 0.05 | 13 | 1.13 | 0.05 |
| Nd | 1.57 | 0.07 | 10 | 1.45 | 0.05 |
| Eu | 0.01 | ... | 0 | 0.52 | 0.06 |
| Fe | 7.45 | 0.01 | 109 | 7.45 | 0.05 |

NOTE: The spectroscopically derived stellar parameters ($T_{\text{eff}}$, log g, $[\text{Fe}/\text{H}]$, $\xi$) and the absolute chemical abundances for the twilight spectrum of the Sun. The parameter, its derived spectroscopic value, and that parameter’s uncertainty from our high resolution twilight spectrum of the Sun is tabulated in columns 1, 2, and 3, respectively. Note that the abundance tabulated here are the absolute abundance, log(X). Column 4 represents the number of lines that were used for the derivation of the solar chemical abundances. Also tabulated are the reference values and their uncertainties in column 5 and 6 taken from Asplund et al. (2000, 2005, for more details).

NOTE: The spectroscopically derived stellar parameters ($T_{\text{eff}}$, log g, $[\text{Fe}/\text{H}]$, $\xi$) and the absolute chemical abundances for the twilight spectrum of the Sun. The parameter, its derived spectroscopic value, and that parameter’s uncertainty from our high resolution twilight spectrum of the Sun is tabulated in columns 1, 2, and 3, respectively. Note that the abundance tabulated here are the absolute abundance, log(X). Column 4 represents the number of lines that were used for the derivation of the solar chemical abundances. Also tabulated are the reference values and their uncertainties in column 5 and 6 taken from Asplund et al. (2005). $^b$ $\xi$ was not used in Asplund et al. (2005), because they use a 3-D model atmosphere of the Sun, which no longer requires the use of the $\xi$ fudge factor (see Asplund et al. 2000, 2005, for more details).

0.05 dex in $[\text{Fe}/\text{H}]$. The mean offset gives us an estimate of the systematic differences between LAMOST and our high resolution analysis while the dispersions provide an estimate of the precision. These offsets and dispersion are not uncommon when comparing high-resolution to low-resolution data sets (e.g. Lee et al. 2008; Boeche et al. 2018) and are only used to zero-point shift all LAMOST $[X/\text{Fe}]$ abundance ratios onto our stellar abundance scale. For metallicity, this zero-point shift amounts to adding +0.10 dex to the $[\text{Fe}/\text{H}]$ derived from LAMOST spectra by Xiang et al. (2019).

In Fig. 4, we show the metallicity distribution for the 42 Psc–Eri stars observed in this work (black line). For completeness, we also show the metallicity distribution for the 40 Psc–Eri stars observed with LAMOST with an additive 0.10 dex systematic offset in order to ensure the LAMOST $[\text{Fe}/\text{H}]$ are on our metallicity scale. With the 42 Psc–Eri stars observed in this work, we find a metallicity distribution that has a peak at –0.03 dex with a dispersion of 0.07 dex. While this confirms the stream metallicity found in Meingast et al. (2019), which showed that the peak $[\text{Fe}/\text{H}]$ was –0.04 dex with 27 stars, we find a significantly lower dispersion by a factor of ~2. While the peak of the metallicity distribution of the stream is found to be ~0.03 dex using the LAMOST values (as expected), the dispersion is significantly larger (~0.15 dex), this is expected due to the lower resolution spectra and thus larger uncertainties with which $[\text{Fe}/\text{H}]$ can be measured.

The dispersion in $[\text{Fe}/\text{H}]$ appears to be driven by a number of outlier stars, namely Gaia DR2 2429059676701547008, which has a $[\text{Fe}/\text{H}] = –0.29$ dex (3σ outlier), and Gaia DR2 2577307864562003456, which has a metallicity of +0.15 dex (2.5σ outlier). These two stars have high-quality astrometric and kinematic information (with parallax uncertainties well below 1%, and RVs that are consistent between Gaia and our high resolution analysis). In Fig. 3, we illustrate the spectral difference between the metal-poor outlier star Gaia DR2 2429059676701547008 and a comparison star with very similar $T_{\text{eff}}$ and log g but whose $[\text{Fe}/\text{H}]$ is more metal-rich near the median value for Psc–Eri. This figure clearly shows that Gaia DR2 2429059676701547008 is significantly more metal-poor (with significantly weaker absorption features) compared to the typical metallicity found in Psc–Eri. We have no reason to believe that either it or Gaia DR2 2577307864562003456 are non-members based on their kinematics and spatial positions; therefore, we choose to keep both stars in this analysis.

We note that Gaia DR2 2577307864562003456 is considered a member by both Meingast et al. (2019) and Röser & Schilbach (2020), where the latter authors claim to do a more conservative kinematic selection of the stream. However, Gaia DR2 2429059676701547008 is only considered a member by Meingast et al. (2019) but is not in Röser & Schilbach (2020). Removing Gaia DR2 2429059676701547008 would lead to a reduction in the overall $[\text{Fe}/\text{H}]$ dispersion to 0.05 dex. If only select those Psc–Eri stars we observed, which have been identified as members in both Röser & Schilbach (2020) and Meingast et al. (2019), we would find an overall $[\text{Fe}/\text{H}]$ dispersion of 0.04 dex with 29 total stars. Additionally, we note that we find a systematic trend between $T_{\text{eff}}$ and $[\text{Fe}/\text{H}]$, which when corrected for, yields a metallicity distribution that is symmetric with a dispersion of 0.04 dex. Together these indicate that it is likely that the actual stream has a σ$[\text{Fe}/\text{H}] \lesssim 0.04$ dex, but larger studies are required.
A similar dispersion of 0.05 dex was measured for 20 members of the Pleiades by Soderblom et al. (2009), using Keck/HIRES spectra analyzed with Spectroscopy Made Easy (SME; Valenti & Piskunov 1996; Valenti & Fischer 2005). Magnetic activity is known to affect absorption line profiles (e.g. see figure 1 in Davis et al. 2017), which hinders precision Doppler searches for exoplanets (Dumusque 2018). Yana Galarza et al. (2019) analyzed spectra for the Class precision Doppler searches for exoplanets (Dumusque 2005). Magnetic activity is known to affect absorption line profiles (e.g., see figure 1 in Davis et al. 2017), which hinders precision Doppler searches for exoplanets (Dumusque 2018). Yana Galarza et al. (2019) analyzed spectra for the ~400-Myr-old solar twin HIP 36515 using an equivalent width based Fe excitation/ionization balance approach with MOOG (Sneden 1973), and found that the derived stellar properties (T_{\text{eff}}, \log g, \xi, and [Fe/H]) correlated with the SHK chromospheric emission index, with [Fe/H] varying by 0.016 dex between SHK = 0.360-0.355. Our Psc-Eri targets are younger than HIP 36515, and so are likely even more active (e.g., Mamajek & Hillenbrand 2008); therefore, the impact of magnetic activity on our chemical abundances might be comparable or even larger.

The above discussion illustrates that (1) a careful revisit of Psc–Eri membership, (2) a larger study of the metallicity distribution of the Psc–Eri stream will be required in the future to confirm (or not) the existence of the [Fe/H] spread (i.e. to determine to what extent the chemical outliers are in fact really apart of the cluster), and (3) the impact of magnetic activity on chemical abundance measurements will need to be further investigated. The second of these will be easily facilitate with the more than 1000 Psc–Eri member identified by Röser & Schilbach (2020).

In Fig. 5, we expand upon Fig. 4, and show how [Fe/H] is distributed across the stream along the X-Y (left panel), X-Z (middle panel) and Y-Z (left panel) projections. We also show in the background all Psc–Eri stream candidates from Meingast et al. (2019), along with marking where there are possible overdensities in the stream. Fig. 5 implies there are no significant spatial metallicity gradients across the stream.

### 4.2 Lithium Depletion and the Young Age of the Psc–Eri Stream

The atmospheric abundance of Lithium (Li), or lack thereof, is one of the key elements to distinguish if the stream is 1 Gyr (suggested by Meingast et al. 2019, using fitting the color magnitude diagram) or younger (suggested by Curtis et al. 2019a, using gyrochronology). The reason the detection of significant Li can be used as an indicator of youth is because it tends to decrease over time. This is because Li is a rather fragile element which, when mixed down into a layer in a star that is roughly 2.5 \times 10^6 K, is burned into heavier elements, and thus destroyed. The Li can be mixed downward either through rotationally-induced mixing, atomic diffusion, and other physical processes (e.g. Michaela 1986; Charbonnel & Talon 2005; Pinsonneault 2010; Soderblom 2010; Ramirez et al. 2012; Jeffries 2014, and references therein). Additionally, the strength of this depletion is expected to vary with mass (and thus T_{\text{eff}} as a proxy for mass on the main-sequence). It has been shown that the abundance of Li, A(Li), as a function of T_{\text{eff}} is expected to decrease with decreasing T_{\text{eff}} both in the Galactic disk (e.g. Ramirez et al. 2012) as well in open clusters (e.g. Boesgaard et al. 1998; Jeffries 2000; Sestito et al. 2003; Cargile et al. 2010; Cumings et al. 2012; Takeda et al. 2013; Martin et al. 2018; Bouvier et al. 2018).

Similar to other studies of Li at optical wavelengths, we measure its atmospheric abundance using the feature at 6708 Å. In Fig. 6, we show the measured absolute abundance of Li, A(Li), for the stars in the Psc–Eri stream as a function of the measured T_{\text{eff}}. For reference, we also show the A(Li) as a function of T_{\text{eff}} for stars in the Galactic Disk (Ramirez et al. 2012), the Pleiades (Bouvier et al. 2018), and the Hayades (Takeda et al. 2013). Fig. 6 illustrates that the A(Li) trend with T_{\text{eff}} follows very closely that observed in the 120 Myr Pleiades. At a given T_{\text{eff}}, the A(Li) within the stream is significantly higher than expected for an older cluster (e.g., the Hayades; Takeda et al. 2013) and thus we can rule out an older age (<200 Myr) for the stream. The A(Li) trend with respect to T_{\text{eff}} (Fig. 6) shows that the Psc-Eri stream is about as young as the Pleiades (≈120 Myr). This result is consistent with the result from Arancibia-Silva et al. (2020) showing the Li depletion pattern most likely implies an age of 125 Myr.

### 4.3 α elements (Mg, Si, Ca, Ti)

The α elements represent those which are formed through the successive fusion of helium nuclei (i.e. α particles) during the later stages nuclear burning in the inner regions of evolved massive stars. In this work, we focus on the α elements: Mg, Si, Ca, and Ti. We note that Ti is often considered an α element because its behavior with respect to metallicity tends to be similar to the other α elements. However, it is sometimes classified as an Fe-peak element from a nucleosynthesis prospective. This is because it likely originates from the decay of 48Cr rather than successive capture of α particles, (e.g. Curtis et al. 2019b). These elements, are thought to be dispersed into the interstellar medium by Type II supernovae (e.g. Nomoto et al. 2013, and references therein).

For a young population of stars (<5 Gyr) near solar metallicity, as the Psc–Eri has been shown to be (e.g., see Fig. 4 and Fig. 6), it is expected that the [Mg, Si, Ca, Ti/Fe] abundance ratios are relatively low or near zero. It might also be expected that if the stars in the Psc–Eri stream are close to α-(-/α and formed together, that they should all have the same chemical abundances (e.g., Bovy 2016; Liu et al. 2016; Ness et al. 2018; Hawkins et al. 2020).

In Fig. 7 we show the [Mg, Si, Ca, Ti/Fe] abundance ratios as a function of [Fe/H] for the Psc–Eri stream (as black circles). For reference, we also show the behavior of the Galactic disk in all elemental abundance ratios (Bensby et al. 2014; Adibekyan et al. 2012; Battistini & Bensby 2015, 2016). We find that the median [Mg, Si, Ca, Ti/Fe] are 0.01, 0.06, 0.07, 0.10 dex, respectively. These abundance ratios indicate that the Psc–Eri stream most resembles the Galactic thin disk, as expected. The dispersion in these elements are all between 0.06-0.09 dex. However since the typical uncertainty for these elements are generally less than 0.05 dex, we do resolve significant abundance dispersions in the α elements.

Similar to [Fe/H] (e.g. see Fig. 5), we also determined...
the gradient of [X/Fe] across the principal axis of the stream. Interestingly, we find that of all of the α elements, there is only a weak but significant (p<0.01) gradient in [Si/Fe] along primary axis of the stream, with a correlation coefficient of 0.40 using data from our high-resolution dataset. This weak gradient persists whether we use our high-resolution data set or use the LAMOST dataset by itself (correlation coefficient of 0.32 with a p ~ 0.05). To illustrate this in Fig. 8, we show how the [Si/Fe] varies across the stream in X-Y (left panel), Y-Z (middle panel), X-Z spatial (right panel) projections. Further testing whether this gradient is astrophysical (or not) will undoubtedly require a significantly larger sample of Psc–Eri stars. This should be possible with the thousands of new candidate stream stars identified in Ratzenböck et al. (2020).

4.4 odd-Z elements (Na, Al, Sc, V, Cu)

The odd-Z elements studied here include Na, Al, Sc, V, and Cu. These elements are formed in a variety of ways. For example, Na is thought to be produced during hydrostatic C burning and during the NeNa cycle for massive stars. It is thought to be dispersed into the interstellar medium both through Type II supernovae and partially through AGB stars. On the other hand, Al is thought to be produced during C and Ne burning as well as the MgAl cycle in massive stars. Al, much like Na, is thought to be dispersed into the interstellar medium via both Type II supernovae and AGB stars (e.g. Samland 1998; Kobayashi et al. 2006; Nomoto et al. 2013). Sc and V are thought to be produced via explosive O and Ne burning, while Cu is largely produced via SNIa and hypernovae but is also produced by secondary phenomena in massive stars and the weak s-process (e.g. Samland 1998; Mishenina et al. 2002; Andrews et al. 2018). However, it is important to note that the nucleosynthesis pathway for the production of many of these elements are not well understood. This is indicated by the large discrepancy between the theoretical predictions of how these elements abundance ratio, [Sc, V, Cu/Fe] vary with [Fe/H].(e.g. Kobayashi et al. 2006; Nomoto et al. 2013, and references therein).

In Fig. 7 we show the behavior of the odd-Z elements [Na, Al, Sc, V, Cu/Fe] as a function of [Fe/H] for the Psc–Eri stream (as black circles). For reference, the behavior of the Galactic disk in all of the studied odd-Z elements with respect to metallicity are also displayed. (Bensby et al. 2014; Adibekyan et al. 2012; Battistini & Bensby 2015, 2016). We find that the median [Na, Al, Sc, V, Cu/Fe] are –0.02, 0.04, 0.00, 0.14, 0.06 dex, respectively. These abundance ratios, similar to the α elements indicate that the Psc–Eri stream resembles the Galactic thin disk. The dispersion in these elements are all between 0.06–0.08 dex. However since the typical uncertainty for these elements are less than 0.06 dex, we resolve significant abundance dispersion in the α elements. We do not find any significant gradient of [Na, Al, Sc, V, Cu/Fe] across the principal axis of the stream.

4.5 Fe-peak elements (Cr, Mn, Co, Ni, Zn)

The Fe-peak elements, while formed in a variety of ways, are largely thought to be ejected into the interstellar medium.
through Type Ia and Type II supernovae and hypernovae (e.g. Samland 1998; Iwamoto et al. 1999; Kobayashi et al. 2006; Kobayashi & Nakasato 2011; Nomoto et al. 2013). For example, Mn, Ni, and Cr is thought to be produced by explosive Si burning in supernovae while Co and Zn are thought to be produced in hypernovae (e.g. see Samland 1998; Kobayashi et al. 2006; Nomoto et al. 2013; Mikolaitis et al. 2017, for a more detailed discussion on the formation of the Fe-peak elements). While these elements were initially thought to largely track Fe, there are some differences. For example, Mn is more produced at significantly higher levels in Type Ia supernovae and thus [Mn/Fe] shows a decreasing trend with increasing [Fe/H] (Gratton 1989; Kobayashi & Nakasato 2011).

In Fig. 7, we show the behavior of the Fe-peak elements [Cr, Mn, Co, Ni, Zn/Fe] as a function of [Fe/H] for the Psc–Eri stream (as black circles). As before, we also show the behavior of the Galactic disk in this figure. We find that the median [Cr, Mn, Co, Ni, Zn/Fe] are 0.08, 0.05, 0.05, −0.03, −0.04 dex, respectively. These abundance ratios indicate that the Psc–Eri stream most resembles the Galactic thin disk. The dispersion in these elements are all between 0.06–0.13 dex. We just (at the ∼1σ level) resolve significant abundance dispersion in the Fe-peak elements. Similarly to the odd-Z elements, we do not find any significant gradient of [Cr, Mn, Co, Ni, Zn/Fe] across the principal axis of the stream.

4.6 Neutron Capture elements (Sr, Y, Zr, Ba, La, Nd, Eu)

The neutron capture elements are thought to form in variety ways. As such, they are often separated in two groups which depend on the formation channel. The first of these is the slow neutron capture (s-process) elements, which include primarily Sr, Y, Zr, Ba, La, and Nd. These are thought to form through the slow neutron capture process in AGB stars and then subsequently ejected through stellar winds. On the other hand the rapid neutron capture process (r-process), which requires a significantly higher neutron flux compared to the s-process, is thought to create much of the Eu in the universe. The r-process site is still under debate but binary neutron stars are currently the favored mechanism (e.g van de Voort et al. 2019). In Fig. 9 we show the behavior of the Fe-peak elements [Sr, Y, Zr, Ba, La, Nd, Eu/Fe] as a function of [Fe/H] for the Psc–Eri stream (as black circles). We find that the median [Sr, Y, Zr, Ba, La, Nd, Eu/Fe] are 0.12, 0.18, 0.08, 0.19, 0.22, 0.07, 0.21 dex, respectively. For reference, we also show these elemental ratios vary as a function of [Fe/H] in the Galactic disk (Bensby et al. 2014; Battistini & Bensby 2015). We find that the Psc–Eri stream is somewhat enhanced in the neutron capture elements Sr, Y, Ba, La, and Eu relative to the Galactic disk.

The dispersion in these elements are significantly larger...
### Table 3. Stellar Atmospheric Parameters and Chemical Abundances of Observed Targets

| Gaia Source ID | Teff | σ(Teff) | log g | σ(log g) | [Fe/H] | σ([Fe/H]) | [Na/Fe] | σ([Na/Fe]) | [N/Fe] | σ([N/Fe]) |
|---------------|------|---------|-------|----------|--------|-----------|---------|------------|--------|-----------|
| 242905967670154708 | 5480 | 30 | 4.80 | 0.22 | -0.29 | 0.01 | 94 | 0.63 | 0.06 | 0.07 | 0.03 | 9 ... |
| 240052878979972636 | 5582 | 30 | 4.70 | 0.25 | -0.03 | 0.01 | 95 | 1.14 | 0.04 | -0.02 | 0.03 | 9 ... |
| 2402286415346897664 | 5088 | 54 | 4.57 | 0.25 | -0.03 | 0.01 | 69 | 1.28 | 0.07 | -0.04 | 0.04 | 9 ... |
| 24690077441287424 | 5641 | 30 | 4.91 | 0.28 | -0.01 | 0.01 | 87 | 1.18 | 0.05 | -0.05 | 0.03 | 7 ... |
| 262365547512872384 | 5847 | 30 | 4.60 | 0.17 | -0.04 | 0.01 | 96 | 1.24 | 0.05 | -0.03 | 0.04 | 9 ... |
| 262550316576360800 | 5658 | 30 | 4.57 | 0.20 | -0.03 | 0.01 | 97 | 0.98 | 0.05 | -0.02 | 0.04 | 10 ... |
| 264938378618270976 | 5045 | 158 | 4.50 | 0.60 | -0.05 | 0.02 | 73 | 1.70 | 0.09 | -0.12 | 0.04 | 8 ... |
| 270210635132490668 | 5698 | 80 | 4.47 | 0.25 | -0.04 | 0.01 | 84 | 1.61 | 0.06 | 0.13 | 0.07 | 9 ... |
| 2708000004223203069 | 5772 | 50 | 4.75 | 0.24 | -0.01 | 0.01 | 90 | 1.21 | 0.05 | 0.00 | 0.05 | 9 ... |
| 2708287457803126940 | 5939 | 30 | 4.65 | 0.21 | -0.04 | 0.01 | 89 | 1.28 | 0.06 | -0.01 | 0.05 | 10 ... |
| 270915864161029312 | 5359 | 64 | 4.69 | 0.40 | -0.00 | 0.01 | 92 | 1.29 | 0.05 | -0.08 | 0.04 | 10 ... |

NOTE: A cut out of a larger online table, which includes the spectroscopically derived stellar parameters (T_{eff}, log g, [Fe/H], σ) and the chemical abundances ([X/Fe]) for the 42 Psc–Eri stream stars observed in this work. The full table will be provided in the online material. The Gaia DR2 source identifier of each star is given in column 1. The stellar parameters and their uncertainties (T_{eff}, σ(T_{eff}), log g, σ(log g), [Fe/H], σ([Fe/H]), [Na/Fe], σ([Na/Fe]), [N/Fe], σ([N/Fe])) are found in columns 2-9, respectively. The chemical abundance ratio for [Na/Fe] is found in column 10 and its uncertainty in column 11. The abundance ratio is determined as the median abundance over all high quality lines of a given element (for Na the number of lines used is listed in column 12). We note that this uncertainty is determined as the dispersion in the [Na/Fe] over all lines used to derive [Na/Fe] divided by the square root of the number of lines used.

than the other studied elements and range between 0.08–0.28 dex. However, we find that the largest dispersion exist in elements where there is typically only one usable line (e.g. Eu, Sr). Nonetheless, we generally find that the that the dispersion in the [X/Fe] abundance ratio for the neutron capture elements are larger, by a factor of ~2, compared to the typical uncertainty. Similarly to the odd-Z elements, we do not find any significant gradient of [Sr, Y, Zr, Ba, La, Nd, Eu/Fe] across the principal axis of the stream.

### 5 DISCUSSION : FORMATION, AGE, AND CHEMISTRY OF THE PSC–ERI STREAM

The Psc–Eri stream of stars flowing through the Galactic disk represents one the the most massive coeval populations of its type in the Solar neighborhood. When it was first discovered by Meingast et al. (2019), it was suggested that its age was consistent with ~1 Gyr. This was based on isochrone fitting of the color–magnitude diagram of the 256 members found. Follow-up work in gyrochronology (Curtis et al. 2019a) and color–magnitude diagram isochrone fitting the...
The atmospheric abundances ratios, [X/Fe], for the observed Psc–Eri stream candidates (black circles) for odd-Z (Na, Al, Sc, V, Cu), $\alpha$ (Mg, Si, Ca, Ti), and Fe-peak (Cr, Mn, Co, Ni, Zn) elements as a function of metallicity. For reference, behavior of each element with respect to metallicity is also shown for the Galactic disk. The reference data for the Galactic disk is taken from Bensby et al. (2014), Adibekyan et al. (2012), Battistini & Bensby (light green circles, 2015).

The X-Y (left panel), X-Z (middle panel), and Y-Z (right panel) projections of the Psc–Eri stream. For reference, the location of the Sun is at 0,0 in all plots. The full stream members from Meingast et al. (2019) are shown as the open gray circles. The gray circle with the LAMOST + 0.08 offset stands for LAMOST + 0.06 offset. The X-Y (left panel), X-Z (middle panel), and Y-Z (right panel) projections of the Psc–Eri stream. For reference, the location of the Sun is at 0,0 in all plots. The full stream members from Meingast et al. (2019) are shown as the open gray circles. The gray circle with the LAMOST + 0.08 offset stands for LAMOST + 0.06 offset.

Figure 7. The atmospheric abundances ratios, [X/Fe], for the observed Psc–Eri stream candidates (black circles) for odd-Z (Na, Al, Sc, V, Cu), $\alpha$ (Mg, Si, Ca, Ti), and Fe-peak (Cr, Mn, Co, Ni, Zn) elements as a function of metallicity. For reference, behavior of each element with respect to metallicity is also shown for the Galactic disk. The reference data for the Galactic disk is taken from Bensby et al. (gray circles, 2014), Adibekyan et al. (red open squares, 2012), Battistini & Bensby (light green circles, 2015).

Figure 8. The X-Y (left panel), X-Z (middle panel), and Y-Z (right panel) projections of the Psc–Eri stream. For reference, the location of the Sun is at 0,0 in all plots. The full stream members from Meingast et al. (2019) are shown as the open gray circles. The gray density in the background is a Gaussian Kernel density estimator the these data. Stars are color-coded by [Si/Fe], where known, either by LAMOST (triangles) or high-resolution spectra from this work (circles). This illustrates a potentially weak gradient in [Si/Fe] across the major axis of the stream.

An expanded list of >1000 members (Röser & Schilbach 2020; Ratzenböck et al. 2020), have indicated that the stream is only ≈120 Myr old. In this work, we have shown that the behaviour of Li with respect to $T_{\text{eff}}$ (see Fig. 6) rules out the older age of the stream and implies that it is only ≈120–200 Myr. This is consistent with a recent result on the Li equivalent widths of 40 GK-type stream members from Arancibia-Silva et al. (2020).

The Psc–Eri stream is thought to be a coherent, coeval young aggregation of stars moving together with a common origin (i.e., formed from a single molecular cloud). This is expected as most stars are thought to form in clustered, possibly spherical-like, configuration (e.g. Lada & Lada 2003, and...
the Psc–Eri stream is observed to have noticeable, the giant molecular cloud(s) that it formed from could ex-
dance dispersions within the Psc–Eri cluster are larger in
other elements. We also find that the measured abun-
dispersion (of 0.07 dex) and dispersions of similar size
find that the Psc–Eri stream has a noticeable, but not large,
spanning 700 pc in space, while the Pleiades is a denser,
Psc–Eri stream is a long cylindrical cigar-shaped object
but is strikingly different in its morphology in that the
these results, taken together, rule out the initial old age
estimate for the Psc–Eri. They also illustrate the power of
studying the detailed chemistry (from Li to Eu) as a way to
further constrain the age and formation of the stream. These
results show that this newly discovered cylindrical-shaped
stream is both young (according to the Li studied here and in
Arancibia-Silva et al. 2020), and that it is also a chemically
interesting laboratory for studying star and planet formation
physics. A detailed chemical analysis of a significantly larger
sample of Psc–Eri stars will be required to not only confirm
but also to determine whether the overdensities along the
stream are unique or being formed from well-mixed gas on
the several hundred parsec scale.

6 SUMMARY
The Psc–Eri stream is a newly discovered coeval popula-
discovered by Meingast et al. (2019). It is was initially
proposed to be 1 Gyr old, containing up to ∼2000 M⊙ (Mein-
gast et al. 2019). More recent studies of the stream, however,
but not large, chemical abundance dispersions especially in
the neutron capture elements (Krumholz & Ting 2018).

(i) It has a metallicity distribution that is peaked at just
below Solar with [Fe/H] = −0.03 dex. Additionally it has
a rather low but measurable, dispersion in metallicity, with
σ[Fe/H] = 0.07 dex. The dispersion is reduced to σ[Fe/H] =
0.04 dex if we restrict the sample to a high-probability
set of Psc–Eri members that have been identified by both
Meingast et al. (2019) and Röser & Schilbach (2020).

(ii) Psc–Eri and the Pleiades are approximately coeval
(∼120 Myr), according to their Teff−A(Li) distributions (see
Fig. 6).

(iii) The stream shows no significant abundance gradients
across the major axis of the stream, except in [Si/Fe]. This
gradient of [Si/Fe] persists in both the LAMOST data and
our high-resolution data as well. Larger studies of the de-
tailed chemistry of this stream are needed to confirm (or
refute) the existence of this gradient.

(iv) The detailed chemistry of the stream matches the
expectations of the local Galactic thin disk; however, some
enhancements are seen in several neutron capture elements
(e.g., in Sr, Y, Ba, and La).

(v) The stream appears to have abundance dispersions
that are larger than the typical 1σ uncertainties for many
elements including [Fe/H].

References therein). However, stellar feedback from massive
stars forming in the stream can disrupt the molecular cloud
that it is forming from causing it to become stream-like or
potentially even completely unbind the initial stellar distrib-
tion (e.g. Tutukov 1978). Regardless, one might expect
the stream to be chemically homogeneous as it is formed
from a common molecular cloud. However, if that molecular
cloud that formed the stream was sufficiently large there
may be chemical differences across the cloud which could
propagate into inhomogeneity in the Psc–Eri stream (e.g.
Krumholz & Ting 2018). This is particularly true in the
neutron capture elements. While we observe some disper-
sion in these elements, their relative uncertainties are also
larger and therefore this is worth a larger exploration with
a larger sample.

Psc–Eri is similar to the Pleiades in age and mass,
but is strikingly different in its morphology in that the
Psc–Eri stream is a long cylindrical cigar-shaped object
spanning 700 pc in space, while the Pleiades is a denser,
more spherically-shaped self-gravitating open cluster. We
find that the Psc–Eri stream has a noticeable, but not large,
[Fe/H] dispersion (of 0.07 dex) and dispersions of similar size
in other elements. We also find that the measured abun-
dance dispersions within the Psc–Eri cluster are larger in
the neutron capture elements. The elongated structure of
the Psc–Eri stream, along with chemical inhomogeneity in
the giant molecular cloud(s) that it formed from could ex-
plain why the Psc–Eri stream is observed to have noticeable,
ACKNOWLEDGEMENTS

This paper includes data taken at The McDonald Observatory of The University of Texas at Austin. We thank the staff at McDonald Observatory for making this project possible. KH has been partially supported by a TDA/Scialog (2018-2020) grant funded by the Research Corporation and a TDA/Scialog grant (2019-2021) funded by the Heising-Simons Foundation. KH acknowledges support from the National Science Foundation grant AST-1907417. KH and ML acknowledge support from the Wooton Center for Astrophysical Plasma Properties under the United States Department of Energy collaborative agreement DE-NA0003843.

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.

Guoshoujing Telescope (the Large Sky Area Multi-Object Fiber Spectroscopic Telescope LAMOST) is a National Major Scientific Project built by the Chinese Academy of Sciences. Funding for the project has been provided by the National Development and Reform Commission. LAMOST is operated and managed by the National Astronomical Observatories, Chinese Academy of Sciences.

REFERENCES

Adibekyan V. Z., Sousa S. G., Santos N. C., Delgado Mena E., González Hernández J. I., Israelian G., Mayor M., Khachatryan G., 2012, A&A, 545, A32
Alvarez R., Plez B., 1998, A&A, 330, 1109
Andrievesky S., Bonifacio P., Caffau E., Korotin S., Spite M., Spite F., Sbordone L., Zhukova A. V., 2018, MNRAS, 473, 3377
Arancibia-Silva J., Bouvier J., Boyo A., Galli P. A. B., Brandner W., Bouy H., Barrado D., 2020, arXiv e-prints, p. arXiv:2002.10556
Asplund M., Nordlund Å., Trampedach R., Steen R. F., 2000, A&A, 359, 743
Asplund M., Grevesse N., Sauval A. J., 2005, in Barnes III T. G., Asplund M., Nordlund Å., Trampedach R., Stein R. F., 2000, Elements in the Universe. pp 375–380 (arXiv:1001.3864), doi:10.20356/C4TG6R
Battistini C., Bensby T., 2015, A&A, 577, A9
Battistini C., Bensby T., 2016, A&A, 586, A49
Bensby T., Feltzing S., Oey M. S., 2014, A&A, 562, A71
Blanco-Cuaresma S., Soubiran C., Heiter U., Jofré P., 2014, A&A, 569, A111
Boeche C., Smith M. C., Grebel E. K., Zhong J., Hou J. L., Chen L., Stello D., 2018, AJ, 155, 181
Boesgaard A. M., Deliyannis C. P., Stephens A., King J. R., 1998, ApJ, 493, 206
Bouvier J., et al., 2018, A&A, 613, A63
Bovy J., 2016, ApJ, 817, 49
Buder S., et al., 2018, preprint, (arXiv:1804.06041)
Chaplin W. J., beds. 2010, ApJ, 725, L111
Charbonnel C., Talon S., 2005, Science, 309, 2189
Cui X.-Q., et al., 2012, Research in Astronomy and Astrophysics, 12, 1197
Cummings J. D., Deliyannis C. P., Anthony-Twarog B., Twarog B., Maderak R. M., 2012, AJ, 144, 137
Hawkins et al. 2020

Sestito P., Randich S., Mermilliod J. C., Pallavicini R., 2003, A&A, 407, 289
Sneden C. A., 1973, PhD thesis, THE UNIVERSITY OF TEXAS AT AUSTIN.
Soderblom D. R., 2010, ARA&A, 48, 581
Soderblom D. R., Laskar T., Valenti J. A., Stauffer J. R., Rebull L. M., 2009, AJ, 138, 1292
Takeda Y., Honda S., Ohnishi T., Ohkubo M., Hirata R., Sadakane K., 2013, PASJ, 65, 53
Tull R. G., MacQueen P. J., Sneden C., Lambert D. L., 1995, PASP, 107, 251
Tutukov A. V., 1978, A&A, 70, 57
Valenti J. A., Fischer D. A., 2005, ApJS, 159, 141
Valenti J. A., Piskunov N., 1996, A&AS, 118, 595
Xiang M.-S., et al., 2017, MNRAS, 467, 1890
Xiang M., et al., 2019, ApJS, 245, 34
Yana Galarza J., et al., 2019, MNRAS, 490, L86
van de Voort F., Pakmor R., Grand R. J. J., Springel V., Gómez F. A., Marinacci F., 2019, arXiv e-prints, p. arXiv:1907.01557

This paper has been typeset from a TeX/LaTeX file prepared by the author.