Detailed Abundances of Planet-hosting Open Clusters. The Praesepe (Beehive) Cluster

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Received 2021 February 12; revised 2021 June 10; accepted 2021 June 21; published 2021 September 29

Abstract

It is not yet fully understood how planet formation affects the properties of host stars, in or out of a cluster; however, abundance trends can help us understand this process. We present a detailed chemical abundance analysis of six stars in Praesepe, a planet-hosting open cluster. Pr0201 is known to host a close-in (period of 4.4 days) giant planet (mass of 0.54 M_⊕), while the other five cluster members in our sample (Pr0133, Pr0081, Pr0208, Pr0051, and Pr0076) have no detected planets according to measurements of radial velocity. Using high-resolution echelle spectra with high signal-to-noise ratio obtained with Keck/HIRES and a novel approach to measurements of equivalent width (XSpect-EW), we derived abundances of up to 20 elements spanning a range of condensation temperatures (T_C). We find a mean cluster metallicity of [Fe/H] = +0.21 ± 0.02 dex, in agreement with most previous determinations. We find most of our elements show an [X/Fe] scatter of ~0.02–0.03 dex and conclude that our stellar sample is chemically homogeneous. The T_C slope for the cluster mean abundances is consistent with zero and none of the stars in our sample exhibit individually a statistically significant T_C slope. Using a planet engulfment model, we find that the planet host, Pr0201, shows no evidence of significant enrichment in its refractory elements when compared to the cluster mean that would be consistent with a planetary accretion scenario.

Unified Astronomy Thesaurus concepts: Star-planet interactions (2177); Exoplanet systems (484); Extrasolar gaseous giant planets (509); Optical observation (1169); High resolution spectroscopy (2096); Open star clusters (1160); Stellar abundances (1577); Planet formation (1241)

Supporting material: machine-readable table

1. Introduction

It has been over a decade now since the discoveries of Meléndez et al. (2009) and Ramírez et al. (2009) suggesting that the formation of our solar system’s planets has imprinted a measurable trend on the elemental abundances of the Sun. This trend, known as the condensation temperature (T_C) trend, can be influenced in various ways depending on the formation and evolution of the planetary system. Planet formation may reduce abundances in refractory elements (T_C > 900 K), imparting a negative trend to abundances versus T_C since refractory-depleted material can still be accreted by the host star during the lifetime of the protoplanetary disk (Saffe et al. 2017). Planets in orbit can also be engulfed by their host star, which in turn could result in a positive slope since the star is accreting refractory-rich material into its outer layers (Mack et al. 2014). The T_C slope can inform us of the amount of planetary material sequestered or accreted and help us determine whether planet formation has occurred in the first place, in cases where planets have not been detected by other means. Planetary signatures and T_C trends have been studied by numerous groups, making use of wide binary systems with at least one known planet in order to take advantage of the assumption that they formed from the same molecular cloud and that any differences in their abundances would be due to planet formation (Ramírez et al. 2011, 2015, 2019; Mack et al. 2014, 2016; Tucci Maia et al. 2014; Biazzo et al. 2015; Saffe et al. 2015, 2017; Teske et al. 2015). In this work, we apply similar methods to another chemically homogeneous stellar population: the Praesepe Open Cluster.

Open clusters are important laboratories for understanding a broad range of astrophysical phenomena. They have been used to study Galactic chemical evolution (Anthony-Twarog et al. 2018; Boesgaard et al. 2020), the structure and evolution of the Galactic disk (MacLean et al. 2015; Reddy et al. 2015), stellar physics (Schuler et al. 2009; Davis et al. 2019), and light element abundances (François et al. 2013; Boesgaard et al. 2016), to name a few. The basis of all these studies is the assumption that open clusters are stellar conglomerates containing coeval stars that form out of a well-mixed molecular cloud. This implies that the stars in a given open cluster are the same age and have the same primordial compositions. These properties allow for the systematic determination of their ages (Sandquist et al. 2016; Maurya & Joshi 2020), distances (González-Díaz et al. 2019; Monteiro & Dias 2019), kinematic properties (Geller et al. 2015; Maurya & Joshi 2020), and detailed compositions (Liu et al. 2016; Lum & Boesgaard 2019). There may be more useful information available about the cluster environment than there would be about a wide binary system, such as more accurate age determinations. A cluster can provide these advantages and many more stars to analyze in the context of exoplanets.

According to Meibom et al. (2013), planets in stellar clusters may be just as likely as planets around field stars, but a cluster environment can also be hostile to the formation of planets, and currently there are only tens of known planets in open clusters (Cai et al. 2019). The main difference between field and cluster stars comes in the effect of the chaotic cluster environment on the formation process (protoplanetary disk) or already formed
systems. O/B stars emit high-energy far-UV photons that can photoevaporate nearby circumstellar disks, limiting timescales for planet formation (Anderson et al. 2013; Haworth et al. 2018; Winter et al. 2018). Stellar flybys are frequent in the first 1–2 Myr after cluster formation and can lead to smaller systems (<5.5 au in size), affecting 12%–20% of stars in the lifetime of a cluster similar to Praesepe (Pfalzner et al. 2018). Flybys can also eject planets from a system with an efficiency of a few percent to ∼10% depending on the semimajor axis of the planet, the mass of the host star, and the age of the cluster (Fujii & Hori 2019). Gas expulsion from stellar winds of massive stars or supernova explosions can cause a cluster to become supervirial and boost ejection rates as the cluster reestablishes virial equilibrium (Zheng et al. 2015). In low-density environments (2000 stars in 1 pc virial radius), survival rates for systems containing multiple Jupiter-sized planets could be about 84% and 90% for Earth-only systems in the first 50 Myr (Cai et al. 2017). Based on estimates of the specific free-floating planet production rate from Pacucci et al. (2013), Praesepe could have produced more than 1500 free-floating planets. Aside from the cluster environment, intrasystem dynamics/evolution will also affect a fraction of surviving planetary systems in ways such as planetary migration (Mayor & Queloz 1995; Lin et al. 1996), the Kozai–Lidov effect (Naoz 2016), and planet–planet scattering (Johansen et al. 2012), depending on the structure of the system. The effectiveness of these mechanisms depends heavily on the size and structure of the cluster.

In this paper, we present the analysis of detailed abundance trends for six stars in Praesepe, a planet-hosting open cluster. In Section 2, we describe our sample, observations/data, and spectral analysis including our novel approach to measuring absorption line equivalent widths (EWs), and we verify our methods. In Section 3, we compare our results to the literature and present the derived stellar abundances and observed trends. In Section 4, we discuss our results in the context of a simple model for how the accretion of Earth-like rocky planets would affect refractory elemental abundances as a function of $T_c$ and atomic number. Finally, we briefly summarize the main conclusions in Section 5.

2. Data and Analysis

2.1. Stellar Sample

Stars in Praesepe are of special interest due to the discovery of planets around a number of its members (Quinn et al. 2012; Cai et al. 2019). Praesepe is home to ∼1000 stars, is relatively close by at 182 pc (Cantat-Gaudin et al. 2018), and has an age of ∼600 Myr (Delorme et al. 2011), making it a strong candidate for high-resolution spectroscopy of main-sequence Sun-like stars. It has the highest metallicity ([Fe/H] = +0.21 ± 0.01 dex) of any nearby open cluster according to D’Orazi et al. (2020), which can increase the likelihood of giant planet formation (Johnson et al. 2010) if the metallicity correlation applies to stars in open clusters.

The six stars in our sample consist of a planet host, Pr0201, and five non-hosts: Pr0133, Pr0081, Pr0076, Pr0051, and Pr0208. The data used in this study are a combination of spectra acquired by our group in 2013 and high-quality Keck Observatory Archive (KOA) spectra taken at an earlier time, all of which are publicly available. While other planet hosts exist within Praesepe, we only acquired data for Pr0201. The derived temperatures (see Sections 2.3 and 2.4) for our stars cover ∼500 K with spectral classes between G5 and F8 shown in Table 1. Half of our stars have temperatures within 100 K of the Sun and the other half are hotter with temperatures ∼6100 K. Five out of the six stars have similar estimates of surface gravity, ranging from 4.34 to 4.44 dex with errors of about 0.10 dex. Pr0133 is an exception, having a much lower surface gravity of 4.18 dex. The metallicity of our stars ranges between 0.16 and 0.26 with an average of +0.21 ± 0.02 dex. In Figure 1, we show fits to the broadband spectral energy distribution (using the methodology of Stassun & Torres 2016) for two of our stars, which are also consistent with our spectral analysis.

2.2. Data Acquisition

Three of the six stars (Pr0201, Pr0051, and Pr0076) were observed on UT 2013 December 9 with the HIRES echelle spectrograph (Vogt et al. 1994) in the $R = \lambda/\Delta\lambda = 72,000$ mode on the 10 m Keck I telescope. We used the kv418 filter combined with the B2 slit setting (0′′574 $\times$ 7′′) and 2 $\times$ 1 binning; the spectra cover a wavelength range of 4600–9000 Å. One exposure was taken for each star, with an integration time of 1200 s for Pr0201 and 2100 s for Pr0051 and Pr0076 individually. The signal-to-noise ratio (S/N) in the continuum near 6700 Å is ∼300 for Pr0201 and Pr0051, and ∼250 for Pr0076.

For the remaining three stars, Pr0133, Pr0208, and Pr0081, we obtained raw data files from the KOA. These spectra, which we will collectively refer to as archive spectra, were taken in UT 2003 January and February belonging to program ID H39aH and H47aH; the data are fully described in Boesgaard et al. (2013). We also obtained an archive spectrum for Pr0076 from the same program to verify that our analysis produces consistent results between these different sets of spectra. In our final results we report the stellar parameters and abundances for Pr0076 from both data sets and adopt the results from data taken in 2013. The archive spectra covered a smaller wavelength range (5650–8090 Å) than our new spectra and were obtained in the $R = 48,000$ mode. One exposure was taken for each star with an integration time of 840 s for Pr0133.

### Table 1

| Name  | $T_{\text{eff}}$ (K) | $\log g$ (cgs) | [Fe/H] | $\xi$ (km s$^{-1}$) |
|-------|---------------------|----------------|--------|---------------------|
| Pr0201 | 6168 ± 35           | 4.34 ± 0.10    | 0.25 ± 0.05 | 1.52 ± 0.06 |
| Pr0133 | 6067 ± 60           | 4.18 ± 0.12    | 0.19 ± 0.06 | 1.74 ± 0.11 |
| Pr0208 | 5869 ± 46           | 4.37 ± 0.13    | 0.26 ± 0.07 | 1.53 ± 0.07 |
| Pr0081 | 5731 ± 42           | 4.44 ± 0.11    | 0.18 ± 0.06 | 1.41 ± 0.06 |
| Pr0051 | 6017 ± 27           | 4.40 ± 0.07    | 0.16 ± 0.03 | 1.54 ± 0.05 |
| Pr0076 (2003) | 5789 ± 72 | 4.48 ± 0.12    | 0.25 ± 0.06 | 1.33 ± 0.04 |
| Pr0076 (2013) | 5748 ± 24 | 4.44 ± 0.07    | 0.22 ± 0.05 | 1.35 ± 0.03 |

Note. Adopted solar parameters: $T_{\text{eff}} = 5777$ K, $\log g = 4.44$, and $\xi = 1.38$ km s$^{-1}$.
Figure 1. Spectral energy distributions for two representative targets in our study sample. Red symbols represent the broadband fluxes drawn from the Galaxy Evolution Explorer (Martin et al. 2003), the AAVSO Photometric All-Sky Survey (Henden et al. 2009), the Two Micron All Sky Survey (Skrutskie et al. 2006), and the Wide-field Infrared Survey Explorer (Wright et al. 2010). The black curve is the best fitting Kurucz atmosphere model. Blue symbols are the model fluxes corresponding to each of the observed passbands. The integrated bolometric fluxes together with the Gaia DR2 parallax (Gaia Collaboration et al. 2018) yields the stellar radii. Left: Pr0201—reduced χ2 = 2.1 and best-fit extinction A_V = 0.072 ± 0.024, resulting in a bolometric flux at Earth of F_{bol} = 1.77 ± 0.03 × 10^{-9} \text{ erg s}^{-1} \text{ cm}^{-2}, giving a radius of R = 1.166 ± 0.022 R_\odot. Right: Pr0051—reduced χ2 = 1.2 and best-fit extinction A_V = 0.07 ± 0.03, resulting in a bolometric flux at Earth of F_{bol} = 1.241 ± 0.029 × 10^{-9} \text{ erg s}^{-1} \text{ cm}^{-2}, giving a radius of R = 1.086 ± 0.019 R_\odot.

Figure 2. Sample Keck/HIRES spectra for Pr0076 and the Sun, spanning a wavelength range of ~6135–6175 Å. The top panel represents the archive data, the middle panel represents data taken in 2013, and the bottom panel shows the solar spectrum used. Marked absorption lines are those measured within this range.

1200 s for Pr0208, 1500 s for Pr0076, and 1500 s for Pr0081. The S/N in the continuum near 6700 Å for these spectra is ~220.

All of the data were reduced consistently using the MAKEE data reduction software. We required a solar spectrum to derive the solar abundances used to determine the abundances of our target stars relative to the Sun. For this purpose, we used the high-quality Keck/HIRES solar spectrum (S/N ~ 800 near 6700 Å) from Schuler et al. (2015) obtained in 2010 June in the R = 50,000 mode over the wavelength range 3750–8170 Å. A sample region of the spectra used is shown in Figure 2 for Pr0076 from both data sets in comparison to the solar spectrum.

2.3. Determination of Abundances and Stellar Parameters

We have derived chemical abundances relative to solar ([X/H]) for up to 20 elements in each of our stars. For our analysis, the adopted solar parameters were T_eff = 5777 K, log g = 4.44, and ξ = 1.38 km s^{-1}. A sample of the adopted line lists, EWs, and log(N) line-by-line abundances for each element is given in Table 2. We derived abundances from measurements of EWs of atomic absorption lines in combination with MOOG, an LTE spectral analysis package (Sneden 1973, version 2014) and ATLAS9 stellar atmosphere models (Kurucz 1993). For the archive spectra, we used an abbreviated line list excluding lines not found in those spectra. To determine the stellar parameters of each star, we require the excitation and ionization balance of FeI and FeII lines. Atomic excitation energies (χ) and transition probabilities (log gf) were taken from Mack et al. (2014). For the odd-Z elements Sc, V, Mn, and Co, hyperfine structure (hfs) effects (Prochaska & McWilliam 2000) are taken into account for strong lines through spectral synthesis incorporating hfs components; the resulting abundances are listed in Table 3. The hfs components were obtained from Johnson et al. (2006), and line lists for regions encompassing each feature were taken from VALD (Piskunov et al. 1995; Kupka et al. 1999). Adopted Sc, V, Mn, and Co abundances were derived from the hfs analysis and lines with EWs where hfs effects are negligible. The general method for abundance and error analysis is detailed in Schuler et al. (2011), with new methods used for our current analysis detailed below.
| Ion | \(\lambda\) (Å) | \(\chi\) (eV) | \(\log gf\) | Solar | Pr0201 | Pr0133 | Pr0208 | Pr0081 | Pr0051 | Pr0076 |
|-----|----------------|--------------|----------|-------|--------|--------|--------|--------|--------|--------|
| C I | 5052.167 | 7.685 | −1.304 | 31.58 | 8.417 | 48.52 | 8.481 | ... | ... | ... | ... |
|     | 5380.337 | 7.685 | −1.615 | 19.37 | 8.444 | 33.17 | 8.531 | ... | ... | ... | ... |
|     | 6587.61 | 8.537 | −1.021 | 12.2 | 8.358 | 28.46 | 8.565 | 20.64 | 8.387 | 20.38 | 8.567 |
|     | 7111.469 | 8.64 | −1.074 | 10.53 | 8.431 | 23.78 | 8.596 | 12.28 | 8.24 | 15.3 | 8.544 |
|     | 7113.179 | 8.647 | −0.762 | 22.81 | 8.563 | 40.39 | 8.642 | 30.76 | 8.842 | 26.88 | 8.581 |
| N I | 7468.313 | 10.336 | −0.189 | 4.18 | 8.131 | 9.48 | 8.195 | ... | ... | ... | ... |
| O I | 3600.304 | 0.0 | −9.72 | 5.10 | 8.838 | 4.96 | 8.930 | ... | ... | ... | ... |
| Na I | 5682.633 | 2.102 | −0.152 | 47.58 | 8.063 | 84.38 | 9.139 | 61.74 | 9.007 | 58.58 | 9.097 |
| Mg I | 4730.029 | 3.436 | −2.523 | 66.13 | 7.802 | 60.68 | 7.927 | ... | ... | ... | ... |
|     | 5711.088 | 3.436 | −1.833 | 103.6 | 7.979 | 98.82 | 7.725 | ... | ... | ... | ... |
|     | 6965.409 | 5.753 | −1.51 | ... | ... | ... | ... | ... | ... | ... | ... |
| Al I | 6696.023 | 3.143 | −1.347 | 37.33 | 6.253 | 69.54 | 6.004 | 77.19 | 8.063 | 85.91 | 8.139 |
| Si I | 5772.149 | 5.082 | −1.358 | 50.81 | 7.213 | 58.97 | 7.445 | 59.77 | 7.384 | 66.03 | 7.466 |
|     | 7405.772 | 5.614 | −0.313 | 89.3 | 7.108 | 100.7 | 7.352 | 102.1 | 7.332 | 104.6 | 7.326 |
|     | 6125.021 | 5.646 | −1.464 | 32.55 | 7.48 | 39.8 | 7.688 | 39.12 | 7.62 | 41.65 | 7.658 |
|     | 6244.466 | 5.616 | −1.093 | 44.9 | 7.316 | 54.31 | 7.54 | 53.57 | 7.477 | 58.57 | 7.539 |
|     | 6243.815 | 5.616 | −1.242 | 44.62 | 7.46 | 53.32 | 7.675 | 55.52 | 7.655 | 57.63 | 7.675 |
|     | 6145.016 | 5.616 | −1.31 | 39.69 | 7.45 | 46.7 | 7.544 | 42.13 | 7.518 | 53.6 | 7.685 |
|     | 6142.483 | 5.619 | −1.295 | 33.85 | 7.339 | 39.73 | 7.522 | 35.73 | 7.397 | 41.73 | 7.495 |
|     | 6848.58 | 5.863 | −1.524 | 17.25 | 7.401 | 21.13 | 7.572 | 19.82 | 7.485 | 23.61 | 7.584 |
|     | 6414.98 | 5.871 | −1.035 | 46.89 | 7.484 | 55.2 | 7.671 | ... | ... | ... | ... |
|     | 7003.569 | 5.964 | −0.937 | 57.28 | 7.606 | 61.99 | 7.74 | 68.65 | 7.794 | 77.06 | 7.873 |
|     | 6741.628 | 5.984 | −1.428 | 15.06 | 7.344 | 20.56 | 7.56 | 19.67 | 7.49 | 22.05 | 7.553 |
|     | 4694.113 | 6.525 | −1.77 | 11.0 | 7.311 | 13.81 | 7.27 | ... | ... | ... | ... |
|     | 4695.443 | 6.525 | −1.92 | 6.13 | 7.167 | 11.15 | 7.307 | ... | ... | ... | ... |
|     | 6757.171 | 7.87 | −0.31 | 14.14 | 7.197 | 34.72 | 7.514 | 28.69 | 7.393 | 23.76 | 7.438 |

(This table is available in its entirety in machine-readable form.)
2.4. User-guided Equivalent Width Measurements

The EW measurement of absorption lines is performed by an in-house user-guided code called eXtract from SPECTra—Equivalent Widths (XSpect-EW), specifically created for this purpose. The general process for measuring EWs of absorption lines for abundance derivations includes three main steps: normalization of the continuum, wavelength shift, and fitting the absorption lines with Gaussian or Voigt profiles to determine the EW of the lines. Each step of the process can be vulnerable to user error if done manually, as detailed in the following subsections, depending on how much care and time is given to each part of the analysis. Ideally, one would take extreme care in each of these parts within a minimal amount of time.

2.4.1. Continuum Normalization

Arguably the most important part of the EW measuring process is the ability to consistently determine the continuum of the spectrum or each spectral order. The differential curve-of-growth (CoG) abundance determination involves comparing the abundances of the star of interest to those of a standard or reference star, often the Sun; therefore, one must be able to determine the continuum in each spectral order in the same way for the star and the standard so as to minimize differences in the abundances that could arise as a result of the analysis. XSpect-EW has been designed to normalize the spectrum efficiently and accurately by using a two-step process.

Step 1: a spectrum is split into smaller pieces (referred to as selection windows), the size of which is set to larger than the typical size of the absorption lines to ensure that the selection windows do not fall entirely within a line. For example, in an optical high-resolution Keck/HIRES spectrum with \( R > 60,000 \), the width of a typical line will be 0.4–0.6 Å, so the size of the selection window could be \( \sim 1.6 \) Å. Points above 90% of the flux values within a selection window are chosen as points in the continuum (90% value can be adjusted by the user if needed).

Step 2: the chosen continuum points are used to normalize the spectrum by fitting them with a Gaussian process (GP). A GP is a collection of random variables, any finite number of which have a joint Gaussian distribution. A square exponential kernel \( \kappa(x, x') = \Lambda \exp[-\Gamma(x - x')^2] \) is used for the covariance function in the GP, where \( \Lambda \) is the variance and \( \Gamma \) is the inverse length scale \( \Gamma = 1/(2\ell^2) \). A variance of similar order of magnitude to the flux values is used \( 10^7 \), along with an inverse length scale of 0.1. After testing various values, these gave the best results for our spectra. XSpect-EW will be updated to automatically determine the values of variance and length scale for each order in a spectrum and to have a variety of kernels available. The flux is then divided by the curve output by the GP (gray curve in Figure 3 top panel), which normalizes the order (Figure 3 bottom panel).

2.4.2. Wavelength Shift

Once normalization is complete, each order is wavelength-shifted to the rest frame. This can be done manually by visually identifying a portion of an order in the observed spectrum,
comparing it to a reference spectrum, and using software to shift the wavelength axis by the appropriate amount. Errors in this part of the process can lead to measuring the wrong lines within an order, which may show up as abundance outliers or result in higher than expected abundance errors later in the analysis.

XSpect-EW makes use of a simple $\chi^2$ minimization approach to this problem. An input spectrum is shifted to match a solar spectrum order by order. This is done by determining the median wavelength value in the order of the spectrum to be shifted, finding in which order in the solar spectrum this value falls, and shifting the order to match the solar spectrum. The shift is determined by evaluating $\chi^2$ between the two orders for a range of wavelength shifts from $-5$ Å to $+5$ Å in steps of 0.1 Å and selecting the shift with the minimum $\chi^2$ value (shift ranges and resolution can be changed by the user if needed). In cases where a shift cannot be determined for an order, the shifts for other orders are used to predict the shift of the missing order by linear interpolation of the shift values. A user may also manually shift any order by a specified amount for further correction if needed.

2.4.3. Equivalent Width Measurements

Measuring the EW of an absorption line generally involves fitting a Gaussian or Voigt function to the line and then integrating that function to determine the area enclosed by the curve and continuum. XSpect-EW uses a four-step process for this.

Step 1: the extent of the line being measured is determined. Carefully determining the extent, or width, of the line at the continuum, is critical to obtaining an accurate measurement of the absorption in the line. A piece of the spectrum around a selected line is trimmed from the rest of the spectrum (default set to 1.5 Å about the line center). The boundaries of the line being measured are determined by utilizing the slope of the flux values within the piece of the spectrum. These values range from a maximum or minimum near the center of the line to zero at the continuum and the core, as shown in Figure 4. Using one half of the standard deviation of the flux slope values, a range of values centered on the continuum is created. After testing various values, one half of the standard deviation gave us best results relative to hand-measured EWs. The boundaries of the absorption line are defined as the points where the slope enters this range from the maximum or minimum values to either edge of the line. At this boundary, the slope values approach zero as the flux values approach the constant continuum.

Step 2: with the boundaries defined, XSpect-EW assumes the continuum is correct and shifts the data outside the boundaries of the line (still within the 1.5 Å line window) to match the continuum, effectively isolating the line to be measured.

Step 3: the isolated absorption line and associated continuum are fed into another GP (same kernel) with a small variance of 1 and large inverse length scale of 100.

Step 4: the GP can produce different realizations of the data, and XSpect-EW uses these to perform a Gaussian fit to the line, repeating the process 100 times and thus producing 100 different EW measurements. The mean and standard deviation are calculated using the 100 measurements of the line. Each absorption line can be plotted and remeasured if needed, with the ability to adjust the local continuum and the center and boundaries of the line.

2.4.4. Verification of Methodology

To verify the robustness of our new EW measuring tool, in Figure 5 we compare EWs of Fe I and Fe II lines measured in our solar spectrum with XSpect-EW and by hand with SPECTRE, a spectral analysis package (Sneden et al. 2012). All differences are $<15\%$, with 80% of Fe lines having differences smaller than 5%. In the remaining elemental lines (not shown here), $\sim70\%$ of lines have differences smaller than 5%. XSpect-EW requires some user input to obtain these measurements, which consists of checking each automatic line fit and remeasuring problematic lines by adjusting extra parameters that characterize the absorption line. We note that this interactive functionality has been built into XSpect-EW for this specific purpose. The scatter in the fractional difference of the line measurements is larger for the other elements, because those lines can generally be more difficult to measure due to the variety in the strength of the lines and proximity to other lines. A well curated line list can be helpful for automatic line fits because strong, isolated absorption lines are easier for XSpect-EW to measure automatically. The quality of the data will also be a deciding factor in the number of lines that need to be remeasured. In this example, 17% of Fe lines and 23% of other elemental lines required remeasuring, greatly reducing the amount of time needed to measure all lines and allowing the user to focus on problematic lines to produce abundances with high precision. Lines that are remeasured are only considered based on visual inspection of the fit, not in comparison to previous measurements, since no comparison would be available when measuring a new star. The average of the Fe absolute abundances derived from the XSpect-EW and SPECTRE EWs, shown in Figure 6, agrees within errors and agrees with the input solar absolute abundance within MOOG of 7.50 dex. For all Fe I and II lines, we see a smaller scatter in the absolute abundances from the XSpect-EW measurements than in the SPECTRE measurements by 0.01 dex. From this we can see that XSpect-EW performs as well as, if not slightly better than, a full set of hand-measured EWs from SPECTRE.

From the Fe I and Fe II abundances derived using the EWs measured with XSpect-EW, we determine an average cluster metallicity for Praesepe of $0.21 \pm 0.02$ dex, which is in good agreement with previous measurements.
agreement with most past works on the cluster metallicity. In Table 4, we show the stellar parameter values in the literature for each star along with our own derived values. Our derived stellar parameters ($T_{\text{eff}}$, $\log G$, [Fe/H]) are also in good agreement with current literature values. The main discrepancy between our stellar parameters and literature values comes from the $\xi$ parameter values, which in general are larger than literature values, likely due to the higher $\xi$ value adopted for the Sun in this work ($1.38$ km s$^{-1}$ here compared to lower values used in other studies) (Pace et al. 2008; Gebran et al. 2019; D’Orazi et al. 2020). A more detailed comparison of individual stars to the literature is presented in Section 3.2.

3. Results

3.1. Derived Stellar Abundances

The derived elemental abundances for our targets are summarized in Table 5. Elements with only one measured absorption line have no mean and therefore no uncertainty in the mean; for those lines we have adopted the total error to be the average total error of all other elements in the star. Some elements in some stars were not measurable due to lack of spectral coverage or removal of lines that were not measurable (due to noise, blending, bad fit, etc.). The errors for all stellar parameters and abundances are symmetric or close to symmetric (where $\pm \sigma_{\text{Total}}$ intervals are equal or close to equal); in all cases we conservatively adopt the larger error, except with surface gravity where we adopt the average error. The resulting differences between the archive data (2003) and our data (2013) for Pr0076 are within error bars for the derived stellar parameters and elemental abundances, as shown in Table 5. Despite the fact that we are using data of differing quality, observing conditions, instrument setup, and time of observation, we are able to produce consistent results, giving us great confidence in our analysis.

Figure 7 shows the abundance versus atomic number for each star and the cluster mean. Most elements have a similar spread about the mean while some ($K$, $Sc$, Co, and Cu) show a larger spread. This larger spread is likely due to the fact that these elements have a low number of lines measured, lines may be weak, noisy, or blended with other nearby lines and thus difficult to measure, or some combination of these factors.

3.1.1. Planet-hosting Star

In order to see whether the planet host, Pr0201, is different from the rest of our sample, we compare the abundances to the cluster mean. Figure 8 shows the difference between Pr0201 and the cluster mean (not including the planet host) for each derived element versus atomic number. Most elements fall between $\pm 0.05$ dex of the cluster mean and are within errors of zero with a few exceptions. The element with the largest
Table 4: Comparison to Literature

| Star ID   | \( T_{\text{eff}} \) (K) | \( \log(G/\text{g cm s}^{-1}) \) | \( \xi \) (km s\(^{-1}\)) | \([\text{Fe/H}]\) (dex) | References |
|-----------|--------------------------|---------------------------------|-----------------------------|--------------------------|-------------|
| Pr0201    | 6168 ± 35                | 4.34 ± 0.10                     | 1.52 ± 0.06                 | 0.23 ± 0.05              | This work   |
| Prae kw 418 | 6174 ± 50               | 4.41 ± 0.10                     | …                           | 0.19 ± 0.04              | Quinn et al. (2012) |
| 6062 ± 110 | 4.44 ± 0.07              | 1.27 ± 0.18                     | 0.24 ± 0.10                 |             | Pace et al. (2008) |
| Pr0133    | 6067 ± 60                | 4.18 ± 0.12                     | 1.74 ± 0.11                 | 0.19 ± 0.06              | This work   |
| Prae kw 208 | 6005 ± 19               | 4.46 ± 0.21                     | 1.05 ± 0.04                 | 0.18 ± 0.03              | Gebran et al. (2019) |
| 5997 ± 60  | 4.38 ± 0.20              | 1.40 ± 0.20                     | 0.12 ± 0.10                 |             | Boesgaard et al. (2013) |
| 5993 ± 110 | 4.45 ± 0.07              | 1.52 ± 0.18                     | 0.28 ± 0.10                 |             | Pace et al. (2008) |
| Pr0208    | 5869 ± 46                | 4.37 ± 0.13                     | 1.53 ± 0.07                 | 0.26 ± 0.07              | This work   |
| N2632-8   | 5977 ± 75                | 4.55 ± 0.15                     | 1.30 ± 0.20                 | 0.25 ± 0.11              | D'Orazi et al. (2020) |
| Prae kw 432 | 5841 ± 73               | 4.40 ± 0.20                     | 1.25 ± 0.20                 | 0.17 ± 0.10              | Boesgaard et al. (2013) |
| Pr0081    | 5731 ± 42                | 4.44 ± 0.11                     | 1.41 ± 0.06                 | 0.18 ± 0.06              | This work   |
| CPrae kw 30 | 5716 ± 45              | 4.57 ± 0.42                     | 1.18 ± 0.04                 | 0.12 ± 0.04              | Gebran et al. (2019) |
| 5675 ± 111 | 4.44 ± 0.20              | 1.07 ± 0.20                     | 0.12 ± 0.10                 |             | Boesgaard et al. (2013) |
| Pr0051    | 6017 ± 27                | 4.40 ± 0.07                     | 1.54 ± 0.05                 | 0.16 ± 0.03              | This work   |
| TYC 1395-668-1 |                  |                                 |                             |                          |             |
| Pr0076    | 5748 ± 24                | 4.44 ± 0.07                     | 1.35 ± 0.03                 | 0.22 ± 0.05              | This work   |
| Prae kw 23 | 5773 ± 53                | 4.56 ± 0.24                     | 1.20 ± 0.04                 | 0.20 ± 0.04              | Gebran et al. (2019) |
| 5699 ± 79  | 4.43 ± 0.20              | 1.10 ± 0.20                     | 0.12 ± 0.10                 |             | Boesgaard et al. (2013) |

3.2. Comparison to Previous Work

An et al. (2007) determined \([\text{Fe/H}]\) of four G-type dwarfs in Praesepe through spectroscopy (equivalent width method) and photometry (photometric metallicity). The mean \([\text{Fe/H}]\) they determined through spectroscopy (+0.11 ± 0.03) was lower than our determined mean metallicity of 0.21 ± 0.02. The \([\text{Fe/H}]\) they determined through photometry (+0.20 ± 0.04) is in much better agreement with our results and most current literature values.

Pace et al. (2008) performed a detailed chemical study of eight elements (Fe, Na, Al, Si, Ca, Ti, Cr, Ni) on 20 solar-type stars in four open clusters, obtaining data with high resolution \((R = 100,000)\) and high signal-to-noise ratio \((S/N = 130)\) for seven stars in Praesepe (with two overlapping stars: Pr0133 and Pr0201). They measure a higher mean Fe abundance of +0.27 ± 0.10, though still within errors of our mean abundance. For Pr0201, all eight elements agree within errors, while Pr0133 shows less agreement. Half of the elements agree with our results (Ca, Ti, Cr, Fe) while the other half (Na, Al, Si, Ni) are higher in abundance than our measurements. Our Al measurement comes from just one absorption line for Pr0133, with the total error being the average of the other elements; this could mean this error is underestimated. It is unclear why there is such a discrepancy in the other elements. All reported mean abundances relative to Fe are within error bars except for O, which is much lower than our determined abundance.

Carrera & Pancino (2011) studied abundances of three giants in Praesepe using the equivalent width method, and while they measure a lower mean \([\text{Fe/H}]\) abundance of +0.16 ± 0.05 dex, this mean does fall within errors of our determined mean. Many of the other abundances relative to Fe (Al, Ca, Co, Cr, Mg, Na, Ni, Sc, Si, Ti, and V) disagree with our results, having higher abundances except in the case of Ti and Ca. This is likely due to the fact that these stars are of different stellar type than ours and the lower measured metallicity would increase the abundance ratios relative to Fe.
Table 5
Stellar Abundances

|        | Pr0076 (2003) | Pr0076 (2013) |
|--------|---------------|---------------|
| [C/H]  | 0.12 ± 0.03   | ± 0.05        |
| [O/H]  | 0.11 ± 0.03   | ± 0.05        |
| [N/H]  | 0.19 ± 0.02   | ± 0.04 ± 0.05 |
| [Mg/H] | 0.14 ± 0.01   | ± 0.03 ± 0.05 |
| [Al/H] | 0.12±...±0.05 | ± 0.01±...±0.05 |
| [Si/H] | 0.20 ± 0.01   | ± 0.04 ± 0.05 |
| [Ca/H] | 0.19 ± 0.02   | ± 0.02 ± 0.05 |
| [Sc/H] | 0.12 ± 0.02   | ± 0.01±...±0.05 |
| [Ti/H] | 0.22±...±0.06 | ± 0.01±...±0.06 |
| [V/H]  | 0.22 ± ±0.05  | ± 0.02±...±0.05 |
| [Cr/H] | 0.20 ± ±0.01  | ± 0.02±...±0.05 |
| [Mn/H] | 0.20±...±0.04 | ± 0.01±...±0.04 |
| [Fe/H] | 0.23 ± 0.01   | ± 0.04±...±0.04 |
| [Co/H] | 0.11 ± ±0.01  | ± 0.04±...±0.04 |
| [Ni/H] | 0.19 ± ±0.01  | ± 0.02±...±0.04 |
| [Zn/H] | 0.15±...±0.05 | ± 0.02±...±0.05 |
| [S/H]  | 0.23 ± ±0.09  | ± 0.02±...±0.04 |
| [Cu/H] | 0.02±...±0.05 | ± 0.01±...±0.05 |
| [K/H]  | 0.34±...±0.05 | ± 0.01±...±0.05 |
| [N/H]  | 0.06±...±0.05 | ± 0.01±...±0.05 |

**Notes.**

* σμ— the uncertainty in the mean.
* σTotal — quadratic sum of σμ and uncertainties due to Teff, log g, and ξ.
Boesgaard et al. (2013) presented chemical abundances of 16 elements (Li, C, O, Na, Mg, Al, Si, Ca, Sc, Ti, V, Cr, Fe, Ni, Y, and Ba) for 11 solar-type stars in Praesepe (with four overlapping stars: Pr0133, Pr0208, Pr0081, and Pr0076) through equivalent width analysis. They determined a mean cluster metallicity of $+0.12 \pm 0.04$ dex, which is lower than our determined mean by 0.09 dex. Abundance ratios for other elements relative to Fe are within 1σ of our measurements except for Al and Sc. In most cases the abundance ratios are higher in value, likely because of the lower mean $[\text{Fe}/\text{H}]$ abundance. In Pr0133, Pr0208, and Pr0076, our study overlaps with 13 elements (excluding Li, Y, and Ba) while Pr0081 overlaps with 12 elements (excluding Mg as well). For Pr0133, all elements agree within errors except for Sc, which was found to be about solar or higher ($0.04 \pm 0.08$ dex) while we derived a subsolar value ($-0.20 \pm 0.08$ dex). For Pr0208, errors are not reported in this study, but most elements agree within our own errors. Two elements that do not agree within our errors are Sc and Ti; however, if the errors on these elements are at all similar to the errors for the other stars reported in Boesgaard et al. (2013) then it is very likely they would agree with our abundances. Abundances for Pr0081 are also presented without errors, and similarly to Pr0208, all derived abundances (Fe, C, O, Na, Al, Si, Ca, Sc, Ti, V, Cr, and Ni) are within our own errors except for Sc. It is also true that if the errors for this star are similar to the other stars, Sc would also fall within the errors. For Pr0076, all 13 elements fall within reported errors.

Gebran et al. (2019) used an automated spectral analysis code (BACCHUS) to determine abundances of 24 elements for five stars in Praesepe (with three overlapping stars: Pr0133, Pr0081, and Pr0076). They report mean abundances for G and K stars separately, $+0.17 \pm 0.04$ and $+0.12 \pm 0.01$ dex respectively. These means are consistent with each other and the literature; the average for G types is consistent with our work. In Pr0133 and Pr0081, our study overlaps with 14 elements (C, O, Na, Mg, Al, Si, Ca, Sc, Ti, V, Cr, Co, Ni, and Cu), all of which agree within errors for Pr0081. For Pr0133, all elements but Na and Cu agree within errors. Our [Na/Fe] abundance is about solar or less ($-0.07 \pm 0.07$ dex) while Gebran et al. (2019) determined an even lower abundance of $-0.35 \pm 0.16$ dex. The reverse is true for Cu: our work derived a very low abundance of $-0.28 \pm 0.09$ dex while Gebran et al.
(2019) derived a solar or higher value of 0.02 ± 0.03 dex. For Pr0076, our study overlaps with 17 elements (Fe, C, O, Na, Mg, Al, Si, Ca, Sc, Ti, V, Cr, Mn, Co, Ni, Cu, and Zn), all of which also fall within reported errors.

D’Orazi et al. (2020) revisited the metallicity of Praesepe, taking high-resolution spectroscopic observations of 10 solar-type dwarf stars, including Pr0208. All eight elements studied (Fe, Na, Mg, Al, Si, Ca, Ti, and Ni) are within errors of our derived abundances for Pr0208. They report a mean metallicity of +0.21 ± 0.01 dex and conclude that Praesepe is the most metal-rich, young open cluster in the solar neighborhood, in remarkable agreement with our results, which also gives confidence in works that report a higher metallicity. Pr0051 has no literature values to be compared to but the general agreement of our results to the literature gives us confidence in those values as well.

Even with similar analyses the literature suggests a large scatter in metallicity for Praesepe; however, each individual work shows a much lower scatter within its respective sample. The scatter within these works (for [X/Fe]), including our own, is largely consistent with what we would expect from open clusters (De Silva et al. 2007; Bovy 2016; Kovalev et al. 2019). This implies that the Praesepe cluster is chemically homogeneous and these works may be self-consistent but they may not all be consistent with each other. As our analyses and precision improve, it seems we may converge on a consistent metallicity for Praesepe. Perhaps a larger sample analyzed consistently could shed more light on the mean and scatter for the cluster.

![Figure 9. Abundance difference between each other star in Praesepe and cluster mean vs. atomic number for all elements. The dashed line denotes zero difference; the average error is shown on the left of each plot and is the ±1σ error with a dot to mark the center.](image-url)
3.3. Chemical Homogeneity of Praesepe

In Table 6 we show the mean, standard deviation, and error in the mean of [X/H] and [X/Fe] abundance for our stars in Praesepe. For most of the elements, the standard deviation and the error in the mean of [X/Fe] are lower than either for [X/H].

A few exceptions are the elements C, N, O, and Zn, which show a lower standard deviation and error in the mean of [X/H]. K shows the same standard deviation and error in the mean in both [X/H] and [X/Fe]. The average standard deviation is ∼0.01 dex lower in [X/Fe] than in [X/H], while the average error in the mean is about the same. In [X/Fe], the standard deviation of most elements is at or below the average of ∼0.02–0.03 dex, well within literature limits on abundance scatter in open clusters (De Silva et al. 2007; Bovy 2016; Kovalev et al. 2019). With this, we verify that the stars in our sample are chemically homogeneous; a larger sample would be required to confirm the chemical homogeneity of Praesepe as a whole. C and N are above the average by ∼0.02 dex. K and Cu are much higher than the average by ∼0.04 and ∼0.06 dex respectively. Looking at the error in the mean, we see a similar separation where most elements are below the average at ∼0.01–0.02 dex, with elements N, K, and Cu being ∼0.03 dex higher than the average. C and Mn are above the mean by ∼0.01 dex or less.

For elements with Z > 19 (Ca, Sc, Ti, V, Cr, Mn, Co, Ni, and Zn), the scatter in both standard deviation and error in the mean is higher for odd-Z elements (Sc, V, Mn) with the exception of Co, which is similar to Ca, Ti, and Cr, but higher than Ni and Zn. This is likely due to the fact that some of these odd-Z elements may have one or two synthetically measured absorption lines for each star to account for hfs effects, along with lines measured normally where hfs effects are negligible.

### Table 6

| [X/Y]     | Mean  | Std   | Error in Mean |
|------------|-------|-------|---------------|
| [C/H]     | 0.082 | 0.045 | 0.02          |
| [C/Fe]    | −0.125| 0.048 | 0.021         |
| [N/H]     | 0.07  | 0.01  | 0.01          |
| [N/Fe]    | −0.125| 0.045 | 0.045         |
| [O/H]     | 0.082 | 0.02  | 0.009         |
| [O/Fe]    | −0.125| 0.029 | 0.013         |
| [Na/H]    | 0.158 | 0.047 | 0.021         |
| [Na/Fe]   | −0.048| 0.024 | 0.011         |
| [Mg/H]    | 0.176 | 0.041 | 0.021         |
| [Mg/Fe]   | −0.036| 0.029 | 0.015         |
| [Al/H]    | 0.145 | 0.037 | 0.016         |
| [Al/Fe]   | −0.062| 0.03  | 0.014         |
| [Si/H]    | 0.165 | 0.03  | 0.014         |
| [Si/Fe]   | −0.042| 0.009 | 0.004         |
| [S/H]     | 0.19  | 0.037 | 0.018         |
| [S/Fe]    | −0.022| 0.026 | 0.013         |
| [K/H]     | 0.248 | 0.084 | 0.042         |
| [K/Fe]    | 0.052 | 0.084 | 0.042         |
| [Ca/H]    | 0.193 | 0.031 | 0.014         |
| [Ca/Fe]   | −0.013| 0.02  | 0.009         |
| [Sc/H]    | 0.083 | 0.056 | 0.025         |
| [Sc/Fe]   | −0.123| 0.036 | 0.016         |
| [Ti/H]    | 0.189 | 0.04  | 0.018         |
| [Ti/Fe]   | −0.017| 0.021 | 0.01          |
| [V/H]     | 0.223 | 0.039 | 0.018         |
| [V/Fe]    | 0.017 | 0.034 | 0.015         |
| [Cr/H]    | 0.223 | 0.03  | 0.014         |
| [Cr/Fe]   | 0.017 | 0.023 | 0.01          |
| [Mn/H]    | 0.193 | 0.058 | 0.041         |
| [Mn/Fe]   | −0.01 | 0.043 | 0.031         |
| [Fe/H]    | 0.207 | 0.033 | 0.015         |
| [Fe/Co]   | 0.153 | 0.056 | 0.025         |
| [Co/Fe]   | −0.053| 0.38  | 0.017         |
| [Ni/H]    | 0.17  | 0.034 | 0.015         |
| [Ni/Fe]   | −0.037| 0.014 | 0.006         |
| [Cu/H]    | 0.075 | 0.112 | 0.05          |
| [Cu/Fe]   | −0.132| 0.104 | 0.047         |
| [Zn/H]    | 0.14  | 0.014 | 0.01          |
| [Zn/Fe]   | −0.063| 0.017 | 0.012         |
| [X/H]_{avg} | 0.043 | 0.021 |
| [X/Fe]_{avg} | 0.035 | 0.018 |

Figure 10. Cluster mean vs. condensation temperature (\(T_c\)) for refractory elements excluding the planet host Pr0201. The average error is shown on the top left and is the ±1σ error with a dot to mark the center.
4.1. Abundance Trends and Condensation Temperature

In the search for signatures of planet formation we specifically focus on trends in refractory elements with $T_C > 900$ K (Meléndez et al. 2009). During early disk evolution, elements with high $T_C$ are expected to condense into solids at shorter distances from the host star, leading to refractory-poor gas and refractory-rich planetesimals. This results in two possible abundance signatures for the host star. The removal of these elements from the protoplanetary disk allows the accretion of the refractory-depleted material onto the host star, which imparts a decreasing trend in the refractory elements with $T_C$. Alternatively, accretion of refractory-rich planetesimals or planets themselves would impart an increasing trend.

In this section we interpret trends in condensation temperature in the context of a planet engulfment model, explained in Mack et al. (2014), based on the addition or removal of material with similar composition to the Earth to/from the convection zone of a solar-type star. The composition of the Earth is taken from McDonough (2001) and solar composition is from Asplund et al. (2009). We adjust the size of the convection zone based on the temperature of the star according to Pinsonneault et al. (2001). Solar abundances are modified to match those of the cluster mean (excluding Pr0201), then we can adjust the number of $M_\oplus$ accreted/sequestered in order to produce a desired $T_C$ slope.

Figure 10 shows the $T_C$ trend for refractory elements of the cluster mean. Here, we have excluded the planet host, Pr0201, to show that the mean cluster abundances alone present no
shown in blue vs. atomic number along with the average different amounts of error in the mean plot and is the mean for refractory elements. The average error is shown on the left side of the planet host.

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Figure 12. \(T_C\) trend of the difference between planet host, Pr0201, and cluster mean for refractory elements. The average error is shown on the left side of the plot and is the ±1\(\sigma\) error with a dot to mark the center.

![Figure 12](image)

Figure 13. Top panel: the refractory cluster mean abundances (excluding Pr0201) are shown in blue vs. \(T_C\) along with simulated abundances (orange) of the addition of 4.42 \(M_⊕\) to the cluster mean, which would produce a statistically significant slope at the 3\(\sigma\) level. Bottom panel: cluster mean abundances are shown in blue vs. atomic number along with the average (solid line) and ± the error in the mean (dashed lines). Green and orange lines denote the addition of different amounts of \(M_⊕\). Purple points show the abundances for Pr0201, the planet host.

![Figure 13](image)

trend with condensation temperature. The cluster mean abundances show a slope of \(-5.98 \times 10^{-6} ± 3.25 \times 10^{-5}\) dex K\(^{-1}\), consistent with zero slope. When comparing each other star with the cluster mean (excluding that star and the planet host from the mean), no star shows a statistically significant trend in refractory elements with condensation temperature (slopes shown in Figure 11).

We will take a closer look at Pr0201, because it is the only known planet host in our sample. Figure 12 shows the \(T_C\) trend for refractory elements in Pr0201 relative to the cluster mean. The best-fit line to these elements gives a negative slope of \(-8.64 \times 10^{-5} ± 6.59 \times 10^{-5}\) dex K\(^{-1}\). While not a statistically significant detection (1.5\(\sigma\)), if taken at face value, this trend could be explained by the sequestering of \(\sim 1.62\ M_⊕\) of material from the convection zone of Pr0201.

Our results for \(T_C\) slope are relative to solar abundances ([X/H]), meaning that a slope consistent with zero tells us the distribution of abundances with respect to \(T_C\) is similar to that of the Sun. Results for the cluster mean \(T_C\) slope are consistent with zero slope, meaning that the abundance distribution of the cluster may be similar to that of the Sun. This could indicate that planet formation for Sun-like stars in the cluster is common or that the cluster initially formed from a cloud with this distribution already in place. The possible discovery of more planets within the cluster could give more weight to the prominent planet-forming case. All six of our analyzed stars, including the known planet host, show a slope consistent with zero when compared to the cluster mean. If planet formation is in fact prevalent, the lack of detected planets in our sample could be due to the difficulty of finding smaller planets or these systems may have lost their planets entirely.

4.2. Limits on Chemical Signatures of Planet Ingestion in Pr0201

The Pr0201 system is host to a gas giant (Pr0201b) with a minimum mass of 0.54 ± 0.039 \(M_⊕\) in a circular orbit (Quinn et al. 2012) of short period (4.4264 ± 0.0070 days). With such a close-in giant planet and a \(T_C\) slope consistent with zero, we investigate the possibility that Pr0201 could have accreted or sequestered refractory-rich material during the planet formation process. Using our planet engulfment model mentioned above, we can place limits on the amount of this material. To do this, we assume Pr0201 formed with the same composition as the cluster mean, starting off with zero slope in the refractory elements. We then add material with the same composition as the Earth until we produce a significant \(T_C\) slope (3\(\sigma\) using the measured error in the \(T_C\) slope for Pr0201) in the refractory elements (shown in the top panel of Figure 13). In order to produce a statistically significant \(T_C\) slope, Pr0201 would have needed to accrete 4.42 \(M_⊕\) of material. In the bottom panel of Figure 13, we show how this would affect the individual refractory elements of the cluster mean, depicted by the orange points and lines, which can be compared to the abundances of Pr0201 in purple. The solid lines show the mean abundance while the dashed lines show ± the error in the mean. This accretion scenario would produce abundances that are noticeably enhanced compared to Pr0201 and can be ruled out at the \(\sim 16.5\sigma\) level. Excluding Ti, V, and Fe, it is also the case that 1.25 \(M_⊕\) of material can be ruled out at the 5\(\sigma\) level, indicated by the green lines. In general, Pr0201 does not seem significantly enhanced in refractory elements when compared to the cluster mean. This analysis focuses on accretion but can also be applied to material sequestered.
5. Conclusion

In this work we have used new Keck/HIRES observations combined with KOA spectra of six G- or F-type stars, one of which hosts a 0.54 \( M_\odot \) giant planet, in the nearby Praesepe cluster to derive detailed solar-relative elemental abundances with a precision of \( \sim 0.05 \) dex. For each star we determined \( T_{\text{eff}} \), log \( g \), [Fe/H], \( \xi \) (microrubulence parameter), and abundances of up to 20 elements (Table 5; Figure 7). We verify that our results are in good agreement with the current literature and determine a mean cluster metallicity of \(+0.21 \pm 0.02 \) dex.

We made use of a new custom-built Python code for EW measurements called Xspeak-EW. The code automatically normalizes each order, wavelength-shifts the orders to the rest frame, and fits a Gaussian profile to each line of interest while allowing the user to edit and rerun any of these processes with specified parameters when necessary. This makes measuring hundreds of lines much faster because many lines can be measured automatically with little user contribution and it helps to remove some user error when manually performing these tasks.

We find no \( T_{\text{eff}} \) trend in the mean cluster abundances (Figure 10). Comparing each star’s individual elemental abundances with the cluster mean abundances we see a negative \( T_{\text{eff}} \) trend in the planet host, Pr0201, of \(-8.64 \times 10^{-5} \pm 6.59 \times 10^{-5} \) dex K\(^{-1}\). According to our planet engulfment model, the slope in Pr0201 corresponds to the sequestering of 1.62 \( M_\odot \) of terrestrial material from the convection zone of the star, which could be an indication of terrestrial planet formation, although no terrestrial planets have been detected for this star. We conclude that Pr0201 likely did not accrete a significant amount of Earth-like material.

As mentioned in the introduction, a natural dependence on cluster size and structure is prominent in determining the strength of the chaotic effects of the cluster environment on planet formation and survival. Praesepe, being an open cluster, contains less mass than a globular cluster, only about \( \sim 600 \pm 19 \) \( M_\odot \) (Adams et al. 2002). Less mass would dictate that fewer O/B stars could initially form, lowering the effects of photoevaporation on disks, stellar winds and supernovae on gas expulsion, and would impart a lower average velocity to the cluster members, lowering the frequency of stellar encounters. Even in high-density environments, short-period planets can survive throughout the lifetime of the cluster (Cai et al. 2019). Cluster environmental effects on planet survivability are still not completely understood; however, the current picture painted by recent studies is one of planet formation being common and most planets surviving the evolution of the cluster (albeit in smaller systems or as free-floating planets, most of which are expected to escape the cluster; e.g., van Elteren et al. 2019). Combined with the high metallicity of Praesepe, we have reason to believe that planets could be abundant in the cluster. Already, studies have found 13 planets in Praesepe and about 30 total planets in open clusters (Cai et al. 2019). Pfalzner & Vincke (2020) reported that our solar system likely formed in a high-mass extended or intermediate-mass compact association like NGC 6611 or Praesepe, due to roughly 10% of solar-type stars experiencing flybys after which a solar system analog would remain. As radial-velocity surveys become more precise, we expect many more planets will be discovered in nearby open clusters.

The authors acknowledge support by NSF AAG AST-1009810 and NSF PPARe AST-0849736. This research has made use of the Keck Observatory Archive (KOA), which is operated by the W. M. Keck Observatory and the NASA Exoplanet Science Institute (NExScI), under contract with the National Aeronautics and Space Administration. This work makes use of the Radial Velocity Simulator accessed through the Astronomy Education at the University of Nebraska-Lincoln website (http://astro.unl.edu). We thank the LSSTC Data Science Fellowship Program which has benefited this work. George Vejar also thanks Karl Jaehnig for his help and support which benefited this work.

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