Phosphorus Abundances in FGK Stars

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Abstract

We measured phosphorus abundances in 22 FGK dwarfs and giants that span $-0.55 < [\text{Fe/H}] < 0.2$ using spectra obtained with the Phoenix high-resolution infrared spectrometer on the Kitt Peak National Observatory Mayall 4 m telescope, the Gemini South Telescope, and the Arcturus spectral atlas. We fit synthetic spectra to the P I feature at 10581 Å to determine abundances for our sample. Our results are consistent with previously measured phosphorus abundances; the average [P/Fe] ratio measured in [Fe/H] bins of 0.2 dex for our stars are within ~1σ compared to averages from other IR phosphorus studies. Our study provides more evidence that models of chemical evolution using the results of theoretical yields are underproducing phosphorus compared to the observed abundances. Our data better fit a chemical evolution model with phosphorus yields increased by a factor of 2.75 compared to models with unadjusted yields. We also found average [P/Si] = 0.02 ± 0.07 and [P/S] = 0.15 ± 0.15 for our sample, showing no significant deviations from the solar ratios for [P/Si] and [P/S] ratios.

Key words: stars: abundances

1. Introduction

Abundance measurements of the light elements, from carbon to argon, are important in the study of nucleosynthesis and galactic chemical evolution. The light elements have been used to study differences in Galactic structure, multiple populations in stellar clusters and used as proxies for metallicity in extragalactic studies. The even elements, in particular, including O, Mg, Si, S, and Ca, and their nucleosynthesis in massive stars have been studied in detail (Nomoto et al. 2013). These even elements are well understood in the context of hydrostatic burning and their yields, coupled with chemical evolution models, successfully predict observed abundance trends (e.g., Nomoto et al. 2013). However, the odd light elements are thought to be produced via other processes and few abundance measurements exist for elements such as P and Cl in stars (Nomoto et al. 2013). This work focuses on the odd element phosphorus, an important element for life (Macía 2005) with still uncertain nucleosynthesis production mechanisms.

Phosphorus has only one stable isotope, $^{31}$P, and is thought to be produced mostly in massive stars through neutron capture on Si isotopes, specifically $^{30}$Si, in hydrostatic carbon and neon burning shells (Woosley & Weaver 1995). Phosphorus abundances have been observed using atomic infrared lines at approximately 10500–10820 Å and atomic lines in the near-UV at 2135–2136 Å. Phosphorus abundances have been derived in planetary nebulae using P III lines located at ~7875 Å (Pottasch & Bernard-Salas 2008; Otsuka et al. 2011) and in damped Lyα systems using ionized phosphorus lines, such as P II line at 1152 Å (Outram et al. 1999; Molaro et al. 2001; Levshakov et al. 2002). Anomalously high phosphorus abundances have been measured using optical phosphorus features in blue horizontal branch stars (Behr et al. 1999), which may be due to diffusion of heavy elements, including P, in the photosphere (Michaud et al. 2008). Molecular forms of phosphorus, such as PO, PN, and CP, have been detected and used to understand phosphorus chemistry in the interstellar medium using features at millimeter and radio wavelengths. For example, phosphorus molecules have been detected in the interstellar medium (Turner & Bally 1987) and in star-forming regions (Fontani et al. 2016; Lefloch et al. 2016). Phosphorus molecules have also been found in the circumstellar envelopes of evolved stars (Milam et al. 2008; Agúndez et al. 2014). Finally, the diffuse interstellar medium has been measured using P II lines at 1125 Å and 1533 Å (Lebouteiller et al. 2005).

Solar phosphorus measurements of the infrared lines using 3D solar models found an abundance of $A(P) = 5.46 ± 0.04$ (Caffau et al. 2007). The infrared lines have been used to determine phosphorus abundances in F and G spectral type stars between $−1.0 < [\text{Fe/H}] < 0.2$ (Caffau et al. 2011, 2016). The P abundance differences in solar twins were examined by Kato et al. (1996). These lines weaken for stars with low abundance and are typically only observed in stars with $[\text{Fe/H}] > −1.0$. The near-UV phosphorus lines, however, can be detected and measured in metal-poor stars (Roederer et al. 2014). These features have been used to measure P abundances in FKG-type stars with metallicities between $−3.3 < [\text{Fe/H}] < −0.2$ (Jacobson et al. 2014; Roederer et al. 2014; Spite et al. 2017). Phosphorus abundances have also been compared to alpha elements; Caffau et al. (2011) found a constant phosphorus-to-sulfur ratio of $[P/S] = 0.10 ± 0.10$ over their metallicity range. The odd, light elements, such as Na, Al, and P, are thought to be produced through neutron capture and their abundances should be sensitive to the neutron flux in massive stars during hydrostatic shell burning (Woosley & Weaver 1995). The neutron flux is dependent on metallicity, and a decreasing ratio of phosphorus to elements not dependent on neutron flux, such as the alpha elements, is expected. The constant $[P/S]$ ratio found by Caffau et al. (2011) suggests P production is insensitive to the neutron excess, and other processes may be important in the nucleosynthesis of phosphorus. This effect is more pronounced at lower metallicities of $[\text{Fe/H}] < −1.0$, and more measurements would confirm the constancy of the $[P/S]$ ratio with metallicity (Caffau et al. 2011).

Current models of phosphorus production do not match the observed abundances. Chemical evolution models currently
Table 1

Summary of Phoenix Observations

| HD Number | UT Date       | Telescope | Spectral Type | J Magnitude (Mag) | S/N |
|-----------|---------------|-----------|---------------|-------------------|-----|
| 20794     | 2016 Dec 15   | 1         | G8III         | 3.032             | 280 |
| 46114     | 2016 Dec 15   | 1         | G8V           | 6.266             | 250 |
| 107950    | 2015 Jun 3    | 2         | G6III         | 3.476             | 110 |
| 120136    | 2015 Jun 6    | 2         | F6IV          | 3.620             | 170 |
| 121560    | 2015 Jun 3    | 2         | F6V           | 5.137             | 160 |
| 124819    | 2015 Jun 3    | 2         | F5            | 6.610             | 160 |
| 126053    | 2015 Jun 3    | 2         | G1.5V         | 5.053             | 140 |
| 120136    | 2015 Jun 4    | 2         | G0            | 6.751             | 140 |
| 121560    | 2015 Jun 3    | 2         | G0IV/V        | 6.295             | 80  |
| 140324    | 2015 Jun 3    | 2         | F8            | 6.788             | 70  |
| 148049    | 2015 Jun 4    | 2         | F8            | 6.355             | 170 |
| 151101    | 2015 Jun 6    | 2         | K0III         | 2.913             | 170 |
| 152449    | 2015 Jun 6    | 2         | F6V           | 6.823             | 60  |
| 160507    | 2015 Jun 6    | 2         | G3III         | 5.169             | 170 |
| 163365    | 2015 Jun 3    | 2         | F8            | 6.788             | 70  |
| 167588    | 2015 Jun 4    | 2         | F8V           | 5.363             | 210 |
| 174160    | 2015 Jun 4    | 2         | F7V           | 5.244             | 270 |
| 186379    | 2015 Jun 4    | 2         | F8V           | 5.741             | 190 |
| 186408    | 2015 Jun 3    | 2         | G1.5Vb        | 5.090             | 190 |
| 191649    | 2015 Jun 3    | 2         | G0            | 6.323             | 150 |
| 193664    | 2015 Jun 4    | 2         | G3V           | 4.879             | 210 |
| 194497    | 2015 Jun 4    | 2         | F6V           | 6.504             | 120 |

Notes. Telescopes: (1) Gemini South Telescope; (2) KPNO Mayall 4 m Telescope.

a Spectral types from the SIMBAD database.
b J-magnitudes from 2MASS (Skrutskie et al. 2006).

We predict subphotospheric phosphorus abundances at [Fe/H] = 0 for the solar neighborhood (Kobayashi et al. 2011). A possible exception is the result obtained by Gibson et al. (2005). Phosphorus yields would have to be increased by factors of 1.5–3 to match the observed [P/Fe] ratios measured in field stars (Cescutti et al. 2012). Additional P production mechanisms have been proposed, such as α-particle capture on 27Al or proton capture on 30Si, to resolve the abundance discrepancy (Caffau et al. 2011).

Additional abundance measurements are therefore necessary to help resolve the issue of the nucleosynthesis of phosphorus. It is uncertain how much yields must be increased to match models, and additional measurements are needed to understand if the [P/Fe] versus metallicity slope of the chemical evolution model accurately fits the data. We measured phosphorus in 22 FGK field dwarfs and giants with metallicities in the range −0.5 ≤ [Fe/H] ≤ 0.2 to test these questions. Section 2 describes the data reduction. The methodology used to determine phosphorus abundances is discussed in Section 3. The results are compared to chemical evolution models in Section 4, and the final conclusions are summarized in Section 5.

2. Observations and Data Reduction

Our sample consists of 19 stars observed using the high-resolution infrared spectrometer Phoenix on the Kitt Peak National Observatory 4 m Mayall telescope, and 2 stars from proposal ID GS-2016B-Q-76 on Gemini South Telescope are also observed using Phoenix. We also measured the phosphorus abundance of Arcturus using the infrared atlas (Hinkle et al. 1995). The full list of stars observed is found in Table 1. Target stars with known atmospheric parameters were chosen because the available wavelength range is narrow (our spectral range spanned only ∼50 Å) and contained too few spectral features to determine atmospheric parameters independently. Also, the targeted P I features are strongest in stars with effective temperatures between ∼4500 K and ∼7000 K. Our dwarf star sample was selected from Bensby et al. (2014), Reddy et al. (2003), and Ramírez et al. (2013). Atmospheric parameters for the sample of dwarf stars were adopted from Ramírez et al. (2013) and Bensby et al. (2014), and additional abundances for Si and S are available from Reddy et al. (2003) for a portion of our sample of stars. Additional giant stars with appropriate atmospheric parameters were chosen from the Pascal catalog (Souffrin et al. 2010). For all stars, the atmospheric parameters were determined spectrophotometrically for each literature source (given in Table 2). Finally, only targets with bright J-magnitudes (J ≤ 7 mag), obtained from 2MASS (Skrutskie et al. 2006), were chosen for observation to ensure a sufficient signal-to-noise ratio to measure weak phosphorus features.

The program stars were observed with the Phoenix infrared spectrometer (Hinkle et al. 1998) at the f/16 focus of the KPNO Mayall 4 m telescope in 2015 June and with Phoenix on Gemini South in 2016 December. The 0.7 arcsecond, four-pixel slit was used, resulting in a spectral resolution of ∼50,000 with both telescopes. Echelle order 53 was selected with a narrowband order sorting filter to observe the wavelength range 1.0570–1.0620 μm. Standard observing procedures for infrared observations were followed (Joyce 1992); each object was nodded between two slit positions in an “ABBA” pattern. Dark and flat-field images were observed at the beginning of each night.

The data reduction was accomplished using the IRAF software suite. The dark images were combined using a median filter with a sigclip rejection algorithm, and the flat images were median combined with an avsigclip rejection algorithm. The combined dark image was subtracted from the combined flat image. Sky contribution, bias, and detector blemishes were removed by subtracting objects from one nod position against the next position (“A” slit position image subtracted from the “B” slit position image and visa versa). After sky subtraction, each object was flat-fielded using a dark corrected, normalized flat-field image. Spectral type A and B standard stars were observed for telluric line removal; however, we found no telluric lines in our spectral region. An atlas of Arcturus also shows no telluric contamination in this spectral range; therefore, no telluric correction was needed (Hinkle et al. 1995). Wavelength calibrations were done using the stellar spectral lines, as few comparison lamp emission lines are available in our narrow wavelength range.

3. Abundance Analysis

3.1. Abundance Analysis

Abundances were obtained using MOOG spectral synthesis software (Sneden 1973; version 2014) with MARCS model atmospheres (Gustafsson et al. 2008). Atmospheric parameters were taken from the literature; a full list of atmospheric parameters and their sources is found in Table 2. Additionally, the synthetic spectrum of HD 120136 was broadened to reflect...
the rotational velocity of $v \sin i = 15.4$ km s$^{-1}$ (Mallik et al. 2003).

Atomic line data for the phosphorus transitions shown in Table 3 were obtained from Berzinhsh et al. (1997) and are identical to those used in Caffau et al. (2011). Atomic line data for a n Si I feature were taken from the Kurucz database. The gf value for the Si I line at 10582 Å was refined by fitting the solar spectrum obtained from the Wallace et al. (1993) atlas and the infrared Arcturus atlas (Hinkle et al. 1995). We adopted solar atmospheric parameters of $T = 5870$ K, log $g = 4.44$, and a microturbulence of 0.75 km s$^{-1}$. Atmospheric parameters for Arcturus were adopted from Ramírez & Allende Prieto (2011). Silicon abundances for the solar spectrum of $A$(Si) = 7.51 and $A$(Fe) = 7.50 were adopted from Asplund et al. (2009); the silicon abundance for Arcturus is from Ramírez & Allende Prieto (2011), the solar phosphorus abundance of $A$(P) = 5.46 is adopted from Caffau et al. (2007), and the solar sulfur abundance of $A$(S) = 7.16 is from Caffau et al. (2011). The solar spectrum synthesis was performed using the atomic data from Table 3 and overplotted on the solar spectrum in Figure 1. The best fit was determined by eye and the log $gf$ value for the Si I line was increased by 0.07 to fit both the solar and Arcturus spectra. The updated log $gf$ value for the Si I line listed in Table 3.

Phosphorus abundances were determined by comparing synthetic spectra to the observed spectra and determining the best fit by eye. Examples of final fits to the spectra are shown in Figure 1. To test the reliability of abundances determined by eye, abundances were re-determined by minimizing the $\chi^2$

between synthetic spectra and the corresponding observation. We found the abundances determined from the $\chi^2$ minimization technique were consistent with those found by eye; the average difference was 0.01 ± 0.05 dex. The largest outlier in this difference is the star HD 163363, which has a difference of −0.12 dex from their $\chi^2$ minimization abundance subtracted from their by-eye abundance. This star has a low signal to noise of 70, and this may be the cause of the discrepancy.

The phosphorus abundance determined from the 10581 Å line was chosen as the final phosphorus abundance because the other feature at 10596 Å was often too weak to determine reliable abundances. For dwarf stars with high S/N measurements, such as HD 174160 (in Figure 1), HD 193664, HD 186379, and HD 167588, the P abundance from the 10596 Å agreed with the P I feature at 10581 Å. However, the fit to the P I feature at 10596 Å does not match the observed Arcturus spectrum in Figure 1. This is likely due to a blend with a weak, unidentified line in cool giants. Final phosphorus abundances are plotted in Figure 2. We find no significant dependence of the phosphorus abundance on temperature for our stars, also shown in Figure 2.

Notes. References: (1) Ramírez & Allende Prieto (2011), (2) Bensby et al. (2014), (3) Hekker & Meléndez (2007), (4) Santos et al. (2013), (5) Ramírez et al. (2013), (6) Wang et al. (2011).

* S abundances from Reddy et al. (2003).

b $\alpha$ Boo.

c Si abundance from Ramírez & Allende Prieto (2011).
3.2. Abundance Uncertainty

Uncertainties in the phosphorus abundances were determined in two ways: first, from uncertainties in the atmospheric parameters and from the fit to the phosphorus features. The uncertainty on the abundance was computed by determining the range of acceptable models by eye; the uncertainty determined this way was typically 0.05. This is consistent with the uncertainty in the $\chi^2$ minimization determined from the abundance difference at the $p = 0.05$ significance level, typically 0.07 dex.

To calculate the uncertainties due to the atmospheric parameters, we re-computed the abundances, varying the model atmosphere considering these uncertainties, fit synthetic spectra to the observed spectra to re-drive abundances, and added all errors found from the differences between the abundance in Table 2 and those computed with the varied atmospheric models, from each atmospheric parameter term in quadrature. The average uncertainty in our model parameters in the dwarf stars from Ramírez et al. (2013) were $\delta T = 49 \pm 14$, $\delta \log g = 0.04 \pm 0.01$, $\delta [\text{Fe/H}] = 0.05 \pm 0.01$, and $\delta \xi = 0.12$ km s$^{-1}$.

Due to the uniformity of the uncertainty conditions, uncertainties were calculated for three stars from Ramírez et al. (2013), final uncertainties found from fitting synthetic spectra were 0.03 dex for temperature, and an uncertainty in abundance of 0.01 was due to $[\text{Fe/H}]$ and 0.01 dex from the microturbulence. The abundance uncertainty from varying the log $g$ was consistent
with 0 dex. Added in quadrature, the total uncertainty due to the atmospheric parameters in phosphorus abundance for stars from Ramírez et al. (2013) was 0.03 dex.

Stars with atmospheric parameters not from Ramírez et al. (2013) had larger uncertainties in their atmospheric parameter with averages of $\delta T = 85 \pm 11$, $\delta \log g = 0.17 \pm 0.06$, $\delta [\text{Fe/H}] = 0.09 \pm 0.01$, and $\delta \xi = 0.20 \text{ km s}^{-1}$ (Hekker & Meléndez 2007; Wang et al. 2011; Santos et al. 2013). The uncertainties from the atmospheric parameters were calculated for each of these stars individually and average uncertainties were found to be 0.08 dex for temperature, 0.04 dex for log $g$, 0.02 for $[\text{Fe/H}]$ changes, and the microturbulence caused an uncertainty 0.01. For all stars, the uncertainties were added together in quadrature, with uncertainties in the fit and the final total uncertainties given in Table 2. The uncertainties on $[\text{P/Fe}]$ include both the uncertainty on the phosphorus abundance and on $[\text{Fe/H}]$: $\pm 0.05$ dex uncertainty for stars from Ramírez et al. (2013) and $\pm 0.09$ dex uncertainty for other sources (Hekker & Meléndez 2007; Wang et al. 2011; Santos et al. 2013), as listed in Table 2.

Our abundance determinations were also performed with the assumptions of LTE and 1D MARCS atmospheric models, plane parallel models for dwarf stars and spherical models for giants. No study of NLTE effects on the phosphorus lines is available; however, Asplund et al. (2009) suggest that NLTE effects should be minimal because the phosphorus lines are expected to behave similarly to Si I lines with similar transitions. Specifically, LTE is approximately valid for the 8693 Å (4p³P₃–4d⁴D₃) and 8694 Å lines Si I lines (4p³P₃–4d⁴D₃) (Chen et al. 2002; Takeda et al. 2005). The effects of 3D stellar models compared to 1D were $\sim 0.03$ when calculating the phosphorus abundance for the Sun (Caffau et al. 2007).

### 3.3. Literature Comparisons

Our silicon abundances can be compared to Si measurements previously derived in 15 stars in common with Reddy et al. (2003). Reddy et al. (2003) had derived different metallicities than Ramírez et al. (2013), and therefore reported [Si/Fe] values reflected both differences in Si and Fe abundances between each sample. The differences in metallicity were removed between the two studies, and the A(Si) values were compared directly. The difference between our measurements and those from Reddy et al. (2003) is $-0.03 \pm 0.11$ dex indicating agreement with scatter. Finally, the star HD 120136 was also studied by Caffau et al. (2011) and our result of $[\text{P/Fe}] = -0.01 \pm 0.09$ is consistent with their measurement, $[\text{P/Fe}] = 0.03 \pm 0.08$.

The two stars, HD 20794 and HD 46114, are consistent with silicon abundances derived by Bensby et al. (2014). Our abundance for HD 20794 is $[\text{Si/Fe}] = 0.25 \pm 0.12$, and the abundance for HD 46114 is $0.1 \pm 0.08$. The abundance from Bensby et al. (2014) for HD 20794 is $0.22 \pm 0.22$, and the abundance for HD 46114 is $0.09 \pm 0.06$.

Our measured phosphorus abundances are consistent with the two data sets from Caffau et al. (2011) and Jacobson et al. (2014) in the high-metallicity range (see Figure 2). Our average
The yields predicted by the enhanced yield model better than the original yield model. To test this, the chemical evolution model’s predicted [P/Fe] values were compared to values derived in our sample and abundances from Caffau et al. (2011). We found that \(\chi^2\) was -17.4 for the model with the original yields and 4.4 for the model with yields increased by 2.75. We therefore find our results are consistent with previous measurements of phosphorus and find chemical evolution models with the predicted yields underproduce P compared to the observations.

4.2. Phosphorus and the Alpha Elements

Additionally, we examined the ratios of [P/Si] and [P/S], the two elements nearest to phosphorus in atomic number. Available sulfur abundances for our stars have also been taken from Reddy et al. (2003). The [S/Fe] ratios from Reddy et al. (2003) have been adjusted for two effects: first, we adjusted their [S/Fe] ratios to account for differences in derived [Fe/H] abundances between our atmospheric parameters from Ramirez et al. (2013) and those of Reddy et al. (2003). Second, the adopted solar abundance from Reddy et al. (2003; \(A(S) = 7.34\)) is different from the adopted solar abundance from Caffau et al. (2011) of \(A(S) = 7.16\). We placed the Reddy et al. (2003) results on the same scale. Finally, we note abundances from the S I lines measured from multiple 8 at \(\sim 6750 \AA\) and from multiple 10 at \(\sim 6050 \AA\) used in Reddy et al. (2003) were calculated using LTE analysis, and these lines likely do not suffer from NLTE effects (Chen et al. 2002).

We find that the phosphorus-to-silicon ratio is consistent with the solar ratio over our metallicity range as shown in Figure 3. The [P/Si] ratio for our abundances is plotted in the upper panel of Figure 3, and we find an average ratio of [P/Si] = 0.02 ± 0.07. [P/S] ratios found in Caffau et al. (2011) are compared to our results plotted in the lower panel of Figure 3. We find an average [P/S] ratio of 0.15 ± 0.15, in agreement with the result from Caffau et al. (2011), who found a ratio of [P/S] = 0.10 ± 0.10 for their sample. Combining our two samples leads to a total ratio of [P/S] = 0.13 ± 0.12.

Our [P/Si] and [P/S] results are also compared to chemical evolution models in Figure 3. The chemical evolution model for phosphorus was adopted from Cescutti et al. (2012), and the yields for S were taken from Kobayashi et al. (2006). The Si yields were adopted from Francois et al. (2004), which are the same yields of Woosley & Weaver (1995) for solar metallicity. Additionally, the nearly constant [P/Si] and [P/S] ratios over the metallicity range of \(-0.45 < [\text{Fe/H}] < 0.2\) may be due to insensitivity of the neutron excess that is thought to form the odd elements. The neutron excess increases with increasing metallicity, as more neutron-rich material is present in the star. An increase with increasing [Fe/H] is expected because the formation of odd elements like Na and Al is partially due to neutron capture, unlike the alpha elements (Woosley & Weaver 1995). Our constant [P/S] ratio is in agreement with Caffau et al. (2011). However, ratios of [Na, Al/Mg] do not sharply decrease until [Fe/H] \(\sim -1\) (Gehren et al. 2006). The strong decrease with decreasing metallicity in the [Na, Al/Fe] ratio is most prominent at [Fe/H] \(\sim -1\) in models as well (e.g., Figure 13 from Kobayashi et al. 2011). Measurements of phosphorus in stars with low metallicities would determine if the neutron excess is important at lower metallicities and if the dependence of [Fe/H] over metallicity is similar to the other odd elements.

The \(^{28}\text{Si}\) isotope, which is thought to be the seed for P production, has also been measured to be higher than predictions from chemical evolution models. The infrared study of SiO in M giant stars found isotope ratios of \(^{28}\text{Si}/^{30}\text{Si}\) to be between \(\sim 20–30\) for their sample of six stars (Tsuji et al. 1994), while chemical evolution models give the \(^{28}\text{Si}/^{30}\text{Si}\) \(\sim 34\) at a [Fe/H] = 0 in the solar neighborhood (Kobayashi et al. 2011). While the predicted ratios are lower than measured by a factor of 1.1–1.3, this difference is not extreme. For an \(A^{(28}\text{Si}) = 7.51\), a ratio of 25 would give an \(A^{(30}\text{Si}) = 6.11\), while a ratio of 35 gives an \(A^{(30}\text{Si}) = 5.97\).
work found a thick disk and high velocity for this star make it a probable member of the thick disk; see Figure 3, and therefore the [P/Fe] ratio may also be high.

**HD 163363:** this star has [P/Si] of 0.35 ± 0.12, which is high when compared to other stars near [Fe/H] ~ 0. The high abundance is due to a low [S/Fe] abundance from Reddy et al. (2003) rather than to a high phosphorus abundance, as this star has a [P/Fe] = 0.13 ± 0.09. The low [S/Fe] abundance contrasts with other alpha-element abundances in HD 163363: [Mg/Fe] = 0.15 ± 0.03 and [Si/Fe] = 0.01 ± 0.05 from Reddy et al. (2003) and our [Si/Fe] ratio of 0.01 ± 0.09. The high sulfur abundance may be a measurement error, as it is only ~3σ from a [P/S] = 0 and less than 2σ away from the average value of [P/S] = 0.15 ± 0.15 found within our sample.

**HD 193664:** the star has a slightly low phosphorus abundance at [P/Fe] = 0.09 ± 0.07. The other alpha elements are [Mg/Fe] = 0 ± 0.03, [Si/Fe] = 0.02 ± 0.05 from Reddy et al. (2003), and our [Si/Fe] = 0.02 ± 0.08. The [P/Fe] abundance is low considering the other alpha elements, but it is consistent with the quoted uncertainties; it is 1.7σ away from the average value of [P/Fe] = 0.03 from its metallicity bin (−0.2 < [Fe/H] < 0) in Table 4.

**HD 194497:** this star has [P/S] = 0.47 ± 0.11. This is due to a low sulfur abundance, since we find a normal [P/Fe] abundance. The [P/S] is 2.9σ from the average value of [P/S] = 0.15 ± 0.15. Other alpha abundances are low in this star; [Mg/Fe] = −0.01 ± 0.03 and [Si/Fe] = 0.03 ± 0.05 from Reddy et al. (2003) and our [Si/Fe] = 0.10 ± 0.08.

### 5. Conclusion

1. We have derived phosphorus and silicon abundances for 22 stars using infrared spectra observed with Phoenix on the KPNO 4 m Mayall telescope, Gemini South Telescope, and for Arcturus using spectra from the infrared Arcturus spectral atlas (Hinkle et al. 1995).
2. We found no systematic difference between [P/Fe] abundances in dwarfs and giants.
3. Our phosphorus abundance results are consistent with the other studies, such as Caffau et al. (2011) and Jacobson et al. (2014). We find an average [P/Fe] ratio of 0.10 ± 0.10 in the metallicity range −0.55 < [Fe/H] < 0.2. Our results are in agreement with Caffau et al. (2011), who found an average abundance of [P/Fe] = 0.08 ± 0.15 for their
sample with metallicities between $-1.0 < [\text{Fe/H}] < 0.2$. We also compared [P/Fe] averages to Caffau et al. (2011) and Jacobson et al. (2014) in metallicity bins with sizes of 0.2 dex. Our average values in the metallicity bins to Caffau et al. (2011) agree in all metallicity bins.

4. Our [P/Fe] measurements do not match the results of chemical evolution models with the most recent nucleosynthesis yields. Instead, our results were more consistent with a chemical evolution model of phosphorus with yields increased by a factor of 2.75.

5. We measured Si abundances from a nearby Si I feature. Our silicon abundances matched literature sources; the average difference for 15 stars with corresponding measurements in Reddy et al. (2003) is $-0.03 \pm 0.11$ dex. We find an average [P/Si] ratio of 0.02 $\pm 0.07$ for our sample of stars.

6. We found a [P/S] ratio of 0.15 $\pm 0.15$ in our sample of stars over the metallicity range $-0.55 < [\text{P/Fe}] < 0.2$, using S abundances from Reddy et al. (2003). This result is consistent with results from Caffau et al. (2011), who found $[\text{P/S}] = 0.10 \pm 0.10$ over their range from $-1 < [\text{P/Fe}] < 0.2$.

7. Other odd light elements, such as Na and Al, are sensitive to the neutron flux and their abundances with respect to the alpha-element decrease. Our constant [P/Si] and [P/S] ratios may imply phosphorus is produced by other processes than neutron capture; however, more abundance measurements at lower-metallicity ranges, such as $[\text{Fe/H}] < -1.0$, where the decrease in Na and Al with decreasing metallicities are most pronounced, are needed to explore this hypothesis.

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**Software**: IRAF, MOOG (v2014; Sneden 1973).

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