A New Technique for Determining Europium Abundances in Solar-Metallicity Stars

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ABSTRACT. We present a new technique for measuring the abundance of europium, a representative r-process element, in solar-metallicity stars. Our algorithm compares LTE synthetic spectra with high-resolution observational spectra using a \( \chi^2 \)-minimization routine. The analysis is fully automated, and therefore allows consistent measurement of blended lines even across very large stellar samples. We compare our results with literature europium abundance measurements and find them to be consistent; we also find that our method generates smaller errors.

1. INTRODUCTION

Every atom heavier than lithium has been processed by stars. Elements of the α-process, iron peak, and r-process have different formation sites, and therefore, understanding the distribution of these elements in nearby stars can lead to a better understanding of the Galaxy’s chemical enrichment history. The r-process site is the least well understood. Europium (Eu) is our choice for an r-process investigation for two reasons: 96% of Galactic europium is formed through the r-process (Burris et al. 2000), and it has several strong lines in the visible portion of the electromagnetic spectrum. In order to provide insight into the Galactic enrichment history, however, europium measurements in very large stellar samples will be needed.

The study of r-process elements is well established in metal-poor stars (e.g., Sneden et al. 2008; Lai et al. 2008; Frebel et al. 2007; Simmerer et al. 2004; Johnson & Bolte 2001), where r-process abundances probe early Galactic history. A handful of studies have measured europium in solar-metallicity stars (e.g., Reddy et al. 2006; Bensby et al. 2005; Koch & Edvardsson 2002; Woolf et al. 1995), but have done so in samples of 50–200 stars. We aim to extend such work to a substantial sample of 1000 stars at solar metallicity, using spectra collected by the California Planet Search (CPS). Such a large sample will require automated analysis.

Our goal in this paper is to establish a new, automated abundance fitting method based on Spectroscopy Made Easy (SME; Valenti & Piskunov 1996), an LTE spectral synthesis code discussed in further detail in § 3. The analysis builds on the framework of the Valenti & Fischer (2005, hereafter VF05) Spectroscopic Properties of Cool Stars (SPOCS) catalog. Our method will yield consistent results across large stellar samples, generating smaller errors than previous analyses.

We begin here with 41 stars that have been examined in the literature, and we include three europium lines: 4129 Å, 4205 Å, and 6645 Å. Our stellar observations are detailed in § 2. We describe the details of our europium abundance measurement algorithm in § 3, compare our values with existing europium literature in § 4, and summarize the results of the study in § 5.

2. OBSERVATIONS

The spectra of the 41 stars included in this study were taken with the HIRES echelle spectrograph (Vogt et al. 1994) on the 10 m Keck I telescope in Hawaii. The spectra date from 2004 January to 2008 September and have resolution \( R \sim 50000 \) and signal-to-noise ratio (S/N) of \( \sim 160 \) near 4200 Å, where the two strongest Eu II lines included in this study are located. The spectra have the same resolution but S/N \( \sim 340 \) at 6645 Å, where a third, weaker Eu II line is located.

The spectra were originally obtained by the CPS with the intention of detecting exoplanets. The CPS uses the same spectrometer alignment each night and employs the HIRES exposure meter (Kibrick et al. 2006), so the stellar observations are extremely consistent, even across years of data collection. For a more complete description of the CPS and its goals, see Marcy et al. (2008). It should be noted that the iodine cell Doppler technique (Marcy & Butler 1992) imprints molecular iodine lines only between the wavelengths of 5000 and 6400 Å, leaving the regions of interest for this study iodine free.

2.1. Stellar Sample

For this study we choose to focus on a subset of stars that have been analyzed in other abundance studies. We compare our measurements with those from Woolf et al. (1995); Simmerer et al. (2004); Bensby et al. (2005); and del Peloso et al. (2005).
We select CPS target stars that have temperature, gravity, mass, and metallicity measurements in the Stellar Properties of Cool Stars (SPOCS) catalog (VF05).

Our initial stellar sample consisted of 44 objects that were members both of the aforementioned studies and the SPOCS catalog, and that were observed by the CPS on the Keck I telescope. Three stars that otherwise fit our criteria, but for which we could only measure the europium abundance in one line, were removed from the sample. They were HD 64090, HD 188510, and HIP 89215. While stellar europium abundances may be successfully measured from a single line, the goal of this study is to establish the robustness of our method, and so we deem it necessary to determine the europium abundance in at least two lines to include a star in our analysis here. We describe our criteria for rejecting a fit in § 3.2.

The 41 stars included in this study have $3.4 < V < 10.0$, $0.50 < B - V < 0.92$, and $5 < d < 75$ pc (Hipparcos; ESA 1997). VF05 determine stellar properties using SME, so it is reasonable to adopt their values for our SME europium analysis. Based on the VF05 analysis, our stars have metallicity $-1.4 < \frac{[M/H]}{[H]} < 0.4$, effective temperature $4940 < T_{\text{eff}} < 6230$, and gravity $3.8 < \log g < 4.8$. It should be noted that throughout this study we use the $[\text{M/H}]$ parameter for a star’s metallicity, rather than the iron abundance $[\text{Fe/H}]$. Our $[\text{M/H}]$ value is taken from VF05, where it is an independent model parameter that adjusts the relative abundance of all metals together. It is not an average of individual metal abundances. The full list of stellar properties, from the Hipparcos and SPOCS catalogs, appears in Table 1.

### 2.2. Co-adding Data

The nature of the radial velocity planet search dictates that most stars will have multiple, and in some cases, dozens of, observations. To take advantage of the multiple exposures, we carefully co-add the reduced echelle spectra where possible. The co-adding procedure is as follows: a 2000 pixel region (approximately half the full order width) near the middle of each order is cross-correlated, order by order, with one observation arbitrarily designated as standard. The pixel shifts are then examined and a linear trend as a function of order number is fit to the pixel shifts. For any order whose pixel shift falls more than 0.4 pixel from the linear trend, the value predicted by the linear trend is substituted. This method corrects outlying pixel shift values, which often proved to be one of a handful of problematic orders where the echelle blaze function shape created a false cross-correlation peak.

Each spectral order is adjusted by its appropriate fractional pixel shift before all the newly aligned spectra are added together. In order to accurately add spectra that have been shifted by noninteger pixel amounts, we use a linear interpolation between pixel values to artificially (and temporarily) increase the sampling density by a factor of 20. After the co-adding, the resultant high S/N multiobservation spectrum is sampled back down to its original spacing.

The number of observations used per star is recorded in the $N_{\text{obs}}$ column of Table 2. The co-adding proved particularly beneficial when fitting the relatively weak Eu II line at 6645 Å. Two sample stellar spectra, from a star with one observation and from a star with 17 observations, are given in Figure 1 as evidence of the S/N advantages of this procedure.

### 3. ABUNDANCE MEASUREMENTS

We use the SME suite of routines for our spectral synthesis, both for fine-tuning line lists based on the solar spectrum (§ 3.1) and for measuring europium in each star (§ 3.2). SME is an LTE spectral synthesis code based on the Kurucz (1992) grid of stellar atmosphere models. In brief, to produce a synthetic spectrum, SME interpolates between the atmosphere models, calculates the continuous opacity, computes the radiative transfer, and then applies line broadening, which is governed by macroturbulence, stellar rotation, and instrumental profile. Consult Valenti & Piskunov (1996) and VF05 for a more in-depth description of SME’s inner workings.

Throughout this study we use SME only to compute synthetic spectra. All fitting is done in specialized routines of our own design, external to SME.

In this section we outline our technique for measuring europium abundances in the set of 41 stars included in this work. In broad strokes, we first determine the atomic parameters of our spectral lines by fitting the solar spectrum (§ 3.1). Then, we use that line list to measure the europium abundance in three transitions (4129 Å, 4205 Å, and 6645 Å); a weighted average of the three transitions determines a star’s final europium value (§ 3.2). Finally, we estimate our uncertainties by adding artificial noise to our data in a series of Monte Carlo trials (§ 3.3). We also here include notes on individual lines (§ 3.4).

#### 3.1. Line Lists

We use relatively broad spectral segments in our europium analysis. The regions centered on the Eu II 4129 Å and 6645 Å lines are 5 Å wide, and the region centered on the Eu II 4205 Å line is 8 Å wide. We find it necessary to use such broad spectral segments in order to fit a robust and consistent continuum in the crowded blue regions.

Line lists are initially drawn from the Vienna Astrophysics Line Database (VALD; Piskunov et al. 1995; Kupka et al. 1999). The VALD line lists, in the regions surrounding all three Eu II transitions, make extensive use of Kurucz line lists.

We apply the original VALD line list to an observed solar spectrum in order to determine the list’s completeness and to adjust line parameters as needed. In the blue, we use the disk-center solar spectrum from Wallace et al. (1998) with the following global parameters: $T_{\text{eff}} = 5770$ K, $\log g = 4.44$, $[\text{M/H}] = 0$, microturbulence $v_{\text{mic}} = 1.0$ km s$^{-1}$, macroturbulence $v_{\text{mac}} = 1.0$ km s$^{-1}$, and for measuring europium in each star (§ 3.2). SME is an LTE spectral synthesis code based on the Kurucz (1992) grid of stellar atmosphere models. In brief, to produce a synthetic spectrum, SME interpolates between the atmosphere models, calculates the continuous opacity, computes the radiative transfer, and then applies line broadening, which is governed by macroturbulence, stellar rotation, and instrumental profile. Consult Valenti & Piskunov (1996) and VF05 for a more in-depth description of SME’s inner workings.

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turbulence $v_{\text{mac}} = 3.6$ km s$^{-1}$, rotational velocity $v \sin i = 0$ km s$^{-1}$, and radial velocity $v_{\text{rad}} = 0$ km s$^{-1}$. These are the same solar parameters adopted in VF05. In the red, we find the Wallace et al. (1998) solar atlas to have insufficient S/N to accurately determine the atomic parameters. At 6645 Å, therefore, we instead compare our line list to the disk-integrated NSO solar spectrum (Kurucz et al. 1984), adjusting $v \sin i$ to 1.6 km s$^{-1}$ because the full solar disk has more substantial rotational broadening.

We find that adjustments to the oscillator strength ($\log gf$) and van der Waals broadening ($\Gamma_v$) parameters are required for the strongest lines in a given wavelength segment, even far from the Eu II line of interest. For example, the Fe I line at 4202 Å has an equivalent width $W = 326$ mÅ in the Sun.

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**TABLE 1**

**Stellar Data**

| Identification | $V$ | $B - V$ | $d$ | $T_{\text{eff}}$ | [M/H]$^b$ | $\log g$ | Ref.$^c$ |
|----------------|-----|---------|-----|----------------|----------|---------|---------|
| HD | HR | HIP | (mag) | (mag) | (pc) | (K) | (cgs) |
| 3795 | 219 | 3185 | 6.14 | 0.72 | 28.6 | 5369 | --0.41 | 4.16 | 1 |
| 4614 | 219 | 3821 | 3.46 | 0.59 | 6.0 | 5941 | --0.17 | 4.44 | 4 |
| 6734 | ... | 5315 | 6.44 | 0.85 | 46.4 | 5067 | --0.28 | 3.81 | 1 |
| 9562 | 448 | 7276 | 5.75 | 0.64 | 29.7 | 5939 | 0.19 | 4.13 | 1.24 |
| 9826 | 458 | 7513 | 4.10 | 0.15 | 33.5 | 6213 | 0.12 | 4.25 | 4 |
| 14412 | 683 | 10798 | 6.33 | 0.72 | 12.7 | 5374 | --0.45 | 4.69 | 1 |
| 15335 | 720 | 11548 | 5.89 | 0.59 | 30.8 | 5891 | --0.20 | 4.07 | 4 |
| 16397 | ... | 12306 | 7.36 | 0.58 | 35.9 | 5788 | --0.35 | 4.50 | 1 |
| 22879 | ... | 17147 | 6.68 | 0.55 | 24.3 | 5688 | --0.76 | 4.41 | 1.24 |
| 23249 | 1136 | 17378 | 3.52 | 0.92 | 9.0 | 5095 | 0.03 | 3.98 | 1 |
| 23439 | ... | 17666 | 7.67 | 0.80 | 24.5 | 5070 | --0.73 | 4.71 | 3 |
| 30649 | ... | 22596 | 6.94 | 0.59 | 29.9 | 5778 | --0.33 | 4.44 | 4 |
| 34411 | 1729 | 24813 | 4.69 | 0.63 | 12.6 | 5911 | 0.09 | 4.37 | 4 |
| 43947 | ... | 30067 | 6.61 | 0.56 | 27.5 | 5933 | --0.28 | 4.37 | 2 |
| 45184 | ... | 32318 | 6.37 | 0.63 | 22.0 | 5810 | 0.03 | 4.37 | 1 |
| 48938 | 2493 | 32322 | 6.43 | 0.55 | 26.6 | 5937 | --0.39 | 4.31 | 4 |
| 84737 | 3881 | 48113 | 5.08 | 0.62 | 18.4 | 5960 | 0.14 | 4.24 | 4 |
| 86728 | 3951 | 49081 | 5.37 | 0.68 | 14.9 | 5700 | 0.11 | 4.29 | 4 |
| 102365 | 4523 | 57443 | 4.89 | 0.66 | 9.2 | 5630 | --0.26 | 4.57 | 2 |
| ... | ... | 57450 | 9.91 | 0.58 | 73.5 | 5272 | --0.41 | 4.16 | 1 |
| 103095 | 4550 | 57393 | 6.42 | 0.75 | 9.2 | 4950 | --1.16 | 4.65 | 3 |
| 109358 | 4785 | 61317 | 4.24 | 0.59 | 8.9 | 5930 | --0.10 | 4.44 | 4 |
| 115617 | 5019 | 64924 | 4.74 | 0.71 | 8.5 | 5571 | 0.09 | 4.47 | 4 |
| 131117 | 5542 | 72772 | 6.30 | 0.61 | 40.0 | 5973 | 0.10 | 4.06 | 2 |
| 144585 | ... | 78955 | 6.32 | 0.66 | 28.9 | 5854 | 0.25 | 4.33 | 1 |
| 156365 | ... | 84813 | 6.50 | 0.65 | 47.2 | 5856 | 0.24 | 4.09 | 1 |
| 157214 | 6458 | 84862 | 5.38 | 0.62 | 14.4 | 5697 | --0.15 | 4.50 | 4 |
| 157347 | 6465 | 85042 | 6.28 | 0.68 | 19.5 | 5714 | 0.03 | 4.50 | 1 |
| 166435 | ... | 88945 | 6.84 | 0.63 | 25.2 | 5843 | 0.01 | 4.44 | 1 |
| 169830 | 6907 | 90485 | 5.90 | 0.52 | 36.3 | 6221 | 0.08 | 4.37 | 1 |
| 172051 | 6998 | 91438 | 5.85 | 0.67 | 13.0 | 5564 | --0.24 | 4.50 | 1 |
| 176377 | ... | 93185 | 6.80 | 0.61 | 23.4 | 5788 | --0.23 | 4.40 | 1 |
| 179949 | 7291 | 94645 | 6.25 | 0.55 | 27.0 | 6168 | 0.11 | 4.34 | 1 |
| 182572 | 7373 | 95447 | 5.17 | 0.76 | 15.1 | 5656 | 0.36 | 4.32 | 1 |
| 190360 | 7670 | 98767 | 5.73 | 0.75 | 15.9 | 5552 | 0.19 | 4.38 | 1 |
| 193901 | ... | 100568 | 8.65 | 0.55 | 43.7 | 5408 | --1.19 | 4.14 | 3 |
| 199960 | 8041 | 103682 | 6.21 | 0.64 | 26.5 | 5962 | 0.24 | 4.31 | 1 |
| 210277 | ... | 109378 | 6.54 | 0.77 | 21.3 | 5555 | 0.20 | 4.49 | 1 |
| 217107 | 8734 | 113421 | 6.17 | 0.74 | 19.7 | 5704 | 0.27 | 4.54 | 1 |
| 222668 | 8969 | 116771 | 4.13 | 0.51 | 13.8 | 6204 | --0.08 | 4.18 | 4 |
| 224383 | ... | 118115 | 7.89 | 0.64 | 47.7 | 5754 | --0.06 | 4.31 | 1 |

$^a$V-magnitude, color index, and parallax-based distance from the Hipparcos catalogue (ESA 1997).

$^b$Stellar parameters previously published in VF05.

$^c$Star included for comparison to the following works: 1—Bensby et al. (2005); 2—del Peloso et al. (2005); 3—Simmerer et al. (2004); 4—Woolf et al. (1995).
and significantly affects the continuum of the 4205 Å region. The \( \log g_f \) parameter controls the line depth while the \( \Gamma_6 \) parameter controls the line shape, so in general the two parameters are orthogonal.

We used the Kurucz \( \log g_f \) values provided by VALD where possible, but adjustments were necessary where line depths were poorly fit. For \( \Gamma_6 \), VALD returns the Barklem et al. (2000) parameters for beryllium through barium (\( Z \) of 4–56), but has no \( \Gamma_6 \) values above \( Z = 56 \). We therefore find it necessary to fit \( \Gamma_6 \) in species heavier than bariuin and in deep features not fit well by VALD values. We take particular care to determine the appropriate \( \log g_f \) and \( \Gamma_6 \) parameters for all lines adjacent to the Eu II line of interest. We find the best value for these parameters with the SME synthesizer by performing a \( \chi^2 \) minimization against the solar spectrum on each parameter.

### Table 2

| Name* | \( N_{\text{obs}} \) | \( 4129 \text{Å} \) | \( 4205 \text{Å} \) | \( 6645 \text{Å} \) | Weighted average* |
|-------|------------------|-----------------|-----------------|-----------------|-----------------|
| 3795  | 2                | 0.07            | 0.06            | 0.13            | 0.07±0.03       |
| 4614  | 2                | −0.17           | −0.19           | −0.24           | −0.18±0.02      |
| 6734  | 6                | −0.02           | −0.06           | 0.01            | −0.03±0.03      |
| 9562  | 3                | 0.11            | 0.14            | 0.08            | 0.12±0.02       |
| 9826  | 1                | 0.10            | 0.13            | 0.09            | 0.12±0.02       |
| 14412 | 70               | −0.28           | −0.15           | −0.16           | −0.24±0.06      |
| 15335 | 2                | −0.13           | −0.10           | −0.08           | −0.12±0.03      |
| 16397 | 1                | −0.21           | −0.20           | −0.22           | −0.21±0.02      |
| 22879 | 27               | −0.55           | −0.50           | −0.57           | −0.54±0.03      |
| 23249 | 34               | 0.05            | 0.26            | 0.24            | 0.17±0.11       |
| 23439 | 24               | −0.43           | −0.36           | −0.47           | −0.38±0.03      |
| 30649 | 3                | −0.13           | −0.11           | −0.13           | −0.12±0.02      |
| 34411 | 70               | 0.12            | 0.13            | 0.11            | 0.13±0.02       |
| 43947 | 6                | −0.21           | −0.19           | −0.21           | −0.20±0.02      |
| 45184 | 95               | 0.01            | −0.03           | 0.02            | 0.00±0.02       |
| 48938 | 2                | −0.30           | −0.28           | −0.41           | −0.30±0.03      |
| 84737 | 7                | 0.14            | 0.14            | 0.14            | 0.14±0.02       |
| 86728 | 46               | 0.06            | 0.11            | 0.10            | 0.09±0.03       |
| 102365| 12               | −0.13           | −0.08           | −0.14           | −0.11±0.03      |

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| Name* | \( N_{\text{obs}} \) | \( 4129 \text{Å} \) | \( 4205 \text{Å} \) | \( 6645 \text{Å} \) | Weighted average* |
|-------|------------------|-----------------|-----------------|-----------------|-----------------|
| 100905 | 9                | ...             | −0.37           | −0.38           | −0.37±0.02      |
| 109358 | 47               | −0.12           | −0.16           | −0.12           | −0.14±0.03      |
| 115617 | 165              | 0.05            | 0.02            | 0.09            | 0.04±0.03       |
| 131117 | 2                | 0.10            | 0.09            | 0.12            | 0.10±0.02       |
| 144585 | 17               | 0.22            | 0.25            | 0.22            | 0.23±0.03       |
| 156365 | 1                | 0.11            | 0.20            | 0.14            | 0.13±0.04       |
| 157214 | 24               | 0.05            | 0.06            | 0.07            | 0.06±0.02       |
| 157347 | 77               | 0.09            | 0.12            | 0.13            | 0.10±0.02       |
| 166435 | 1                | −0.05           | −0.17           | 0.04            | −0.07±0.06      |
| 169830 | 8                | 0.02            | 0.05            | 0.05            | 0.03±0.02       |
| 172051 | 37               | −0.19           | −0.15           | −0.12           | −0.17±0.03      |
| 176377 | 56               | −0.20           | −0.21           | −0.23           | −0.20±0.02      |
| 179949 | 1                | 0.05            | 0.02            | 0.05            | 0.04±0.03       |
| 182572 | 56               | 0.25            | 0.41            | 0.36            | 0.31±0.08       |
| 190360 | 73               | 0.17            | 0.29            | 0.30            | 0.24±0.07       |
| 193901 | 2                | −0.92           | −0.91           | −0.98           | −0.91±0.02      |
| 199960 | 3                | 0.14            | 0.19            | 0.19            | 0.16±0.03       |
| 210277 | 74               | 0.20            | 0.34            | 0.32            | 0.27±0.07       |
| 217107 | 37               | 0.20            | 0.43            | 0.33            | 0.29±0.11       |
| 222368 | 2                | 0.08            | 0.09            | 0.08            | 0.08±0.02       |
| 224383 | 2                | 0.00            | −0.01           | 0.04            | 0.00±0.02       |
| Vesta  | 3                | −0.04           | 0.00            | 0.00            | −0.03±0.03      |

*All names are HD numbers unless otherwise indicated.

*For a given star, \[ \text{[Eu/H]} = \log \epsilon(\text{Eu}) - \log \epsilon(\text{Eu})_{\odot} \], where \( \log \epsilon(X) = \log_{10}(N_X/N_H) \).

*The weight of each line in the average is based on 50 Monte Carlo trials in each Eu II line. We have adopted an error floor of 0.02 dex, added in quadrature to the errors determined by our Monte Carlo procedure. See § 3.3 for a more complete description of the weighted average and associated uncertainty.
Like other spectral fitting packages, SME has no built-in treatment of hyperfine structure. We therefore convert a single europium line into its constituent hyperfine components and include them as separate entries in the star’s line list. The relative strengths and wavelength offsets of the hyperfine components come from Ivans et al. (2006), which bases the values on an FTS laboratory analysis. Following the procedure of Ivans et al. (2006), we assume a solar system composition for the relative abundance of the two europium isotopes ($^{151}$Eu at 47.8% and $^{153}$Eu at 52.2%, from Rosman & Taylor 1998). We divide the Eu II $\log gf$ values listed in Tables 3, 4, and 5 amongst the hyperfine components according to their relative strengths. All other attributes of the Eu II lines remain the same in the creation of the hyperfine lines. The relative strengths of the hyperfine components are displayed in the inset plots in the solar spectrum Figures 2, 3, and 4.

### 3.2. Europium Abundances

In order to measure the europium abundances in our selected stars, we begin with the co-added spectra described in § 2.2. We do a preliminary continuum fit using the SME routines, which follow the VF05 procedure: deep features are filled in with a median value from neighboring spectral orders, then a sixth-order polynomial is fit to the region of interest. The built-in procedure creates a flat, normalized continuum, though we find it necessary to fine-tune the continuum normalization in the course of our europium fitting.

From the VF05 SPOCS catalog we take $T_{\text{eff}}$, $\log g$, [M/H], $v\sin i$, $v_{\text{max}}$, and $v_{\text{mic}}$ (fixed at 0.85 km s$^{-1}$) for each star we consider. In general, the global parameters from VF05 agree very well with the values adopted in the studies we compare to here. (Most of the literature values fall within the 2-σ errors quoted in VF05.) The VF05 catalog is one of the largest and most reliable sources of stellar properties determined to date; Haywood (2006), for example, finds the VF05 $T_{\text{eff}}$ and [M/H] to be in good agreement with other reliable measurements.

For most element abundances we use a scaled solar system composition, shifting the Grevesse & Sauval (1998) solar abundances by the star’s [M/H]. The exceptions to this rule are sodium, silicon, titanium, iron, and nickel, which VF05 measured individually. Those α and iron-peak elements are therefore treated independently of the naïve scaled-solar adjustment. It is possible that a more explicit treatment of iron-peak and α elements would improve our europium measurement accuracy. For the present study, however, we deem individual abundance analysis (apart from europium) unnecessary. We hold fixed the abundances of all elements other than europium in the subsequent analysis.

We fit for the europium abundance by iterating three $\chi^2$-minimization routines that solve for the wavelength alignment, spectrum continuum, and europium abundance. A summary of each routine follows:

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1 See http://kurucz.harvard.edu/LINELISTS/LINESMOL/.
1. Wavelength. The pixel scale is predetermined from the thorium lamp calibration taken each night. A first estimate of the rest frame wavelengths comes from a cross-correlation of the full spectral segment with the solar spectrum, a built-in functionality of SME. We then use a 2 Å region immediately surrounding the Eu II line of interest to perform a $\chi^2$ minimization between the modeled stellar atmosphere and the spectral data, thus solving for the wavelength scale alignment as precisely as possible in the Eu II region.

2. Continuum. We fit a quadratic function across the points designated in the solar spectrum as continuum-fitting points (the cross-hatch regions in Figs. 2, 3, and 4). We adjust the quadratic continuum function vertically to require that 1–2% of spectral points in the full spectral segment are above unity, thereby ensuring that all spectra are scaled identically.

3. Abundance. We perform a $\chi^2$ minimization adjusting only the abundance of europium. We begin with the solar abundance value scaled by the star’s metallicity, then search 1.0 dex of europium abundance space to find the best-fit value. In minimizing the $\chi^2$ statistic, we calculate the residuals between the data and the fit in a limited region around the Eu II line (the gray regions in Figs. 2, 3, and 4).

The wavelength alignment, spectrum continuum, and europium abundance fitting routines are run in that order and iterated until a stable solution is reached. In most cases a stable solution requires only one or two iterations. The abundances for each line in each star as determined by this process are listed in Table 2.

After running our automatic europium fitting algorithm on all 41 stars, we examine each line in each star by eye to confirm that the fit is successful. In a few of the metal-poor 4129 Å fits, the blended lines that encroach on Eu II were too weak to be seen in the noise, and hence the output of the fitting routine serves only as an upper limit on the europium abundance.

### Table 3

| $\lambda$ (Å) | Element | Lower level (eV) | $\log gf$ | $\Gamma_0$ |
|---------------|---------|------------------|-----------|------------|
|               | Solar fit | VALD$^a$ | Solar fit | VALD$^a$ |
| 4129.147      | Pr II    | 1.039           | -0.100    | -0.100     | -7.454   | ... |
| 4129.159      | Cr I     | 3.013           | -1.948    | -1.948     | -6.964   | -7.362 |
| 4129.159      | Ti II    | 1.893           | -2.300    | -1.730     | -6.900   | -7.908 |
| 4129.166      | T II     | 2.318           | -0.200    | -0.231     | -6.900   | -7.572 |
| 4129.174      | Ce II    | 0.740           | -3.000    | -0.901     | -7.493   | ... |
| 4129.182$^a$  | Cr I     | 2.914           | -0.100    | ...        | -8.300   | ... |
| 4129.220      | Fe I     | 3.417           | -3.500    | -2.030     | -6.857   | -7.255 |
| 4129.220      | Sm II    | 0.248           | -1.123    | -1.123     | -7.536   | ... |
| 4129.425      | Dy II    | 0.538           | -0.522    | -0.522     | -7.554   | ... |
| 4129.426      | Nb I     | 0.086           | -0.780    | -0.780     | -7.462   | ... |
| 4129.458      | Fe I     | 3.396           | -1.950    | -1.970     | -6.863   | -7.206 |
| 4129.522$^a$  | Fe I     | 3.140           | -3.497    | ...        | -6.873   | ... |
| 4129.643      | T II     | 2.239           | -1.987    | -1.987     | -7.529   | -7.529 |
| 4129.705      | Eu II    | 0.000           | +0.260    | +0.173     | -7.174   | ... |
| 4129.817      | Co I     | 3.812           | -1.808    | -1.808     | -6.099   | -7.782 |
| 4129.837      | Nd II    | 2.024           | -0.543    | -0.543     | -6.237   | ... |
| 4129.959$^a$  | Fe I     | 2.670           | -3.139    | ...        | -7.322   | ... |
| 4130.035      | Fe I     | 1.557           | -3.900    | -4.345     | -7.885   | -7.826 |
| 4130.036      | Fe I     | 3.111           | -2.350    | -2.636     | -8.026   | -7.857 |
| 4130.073      | Cr I     | 2.914           | -1.971    | -1.971     | -6.929   | -7.349 |
| 4130.122$^a$  | V I      | 1.218           | -1.000    | -3.142     | -7.060   | -7.800 |
| 4130.233      | Mn I     | 2.920           | -2.400    | -3.309     | -7.900   | -7.784 |
| 4130.315      | V I      | 2.269           | -0.300    | -0.607     | -7.187   | -7.585 |
| 4130.364      | Gd II    | 0.731           | +0.177    | -0.090     | -6.608   | ... |
| 4130.425      | Cr I     | 2.914           | -1.099    | -2.751     | -6.805   | -7.348 |

$^a$ All line data except $\Gamma_0$ from Kurucz databases via VALD (unless otherwise noted).
$^b$ Van der Waals parameters where available from Barklem et al. (2000) via VALD (unless otherwise noted).
$^c$ Identification from Moore et al. (1966), $\log gf$ and $\Gamma_0$ from $\chi^2$ minimization.
$^d$ Artificial iron lines included after del Peloso et al. (2005).
$^e$ Identification and parameters from Kurucz line lists hosted by the University of Hannover: http://www.pmp.uni-hannover.de/cgi-bin/ssi/test/kurucz/sekur.html.
abundance. See Figure 5 for a comparison of a measureable 6645 Å feature and a feature that provides an upper limit. In the cases where the 6645 Å line is an upper limit only, it is listed as such in Table 2 and does not contribute to the average.

If both 4129 Å and 6645 Å proved problematic, we removed the star from our analysis entirely. The three stars for which this was the case (listed in § 2.1) are omitted from Tables 1 and 2. Since all of the rejected stars were metal poor, we conclude that our fitting routine is most robust at solar metallicity, and becomes less reliable at [M/H] < −1. Temperature may also play a role, as one of the rejected stars, HD 64090, has T_eff = 7300 K; VF05 determined SME to be reliable between 4800 and 6500 K.

**TABLE 4**

**LINE LIST FOR THE REGION NEAR EU II AT 4205 Å**

| λ (Å) | Element | Lower level (eV) | log g_f | Solar fit | VALD | Solar fit | VALD |
|-------|---------|-----------------|---------|-----------|------|-----------|------|
| 4204.695 | Y II | 0.000 | −1.800 | −1.760 | −7.700 | ... |
| 4204.717 | Ce II | 0.792 | −0.963 | −0.963 | −7.000 | ... |
| 4204.759 | CH | 0.519 | −1.140 | −1.158 | −8.900 | ... |
| 4204.771 | CH | 0.520 | −1.900 | −1.135 | −8.500 | ... |
| 4204.801 | Sm II | 0.378 | −1.771 | −1.771 | −6.738 | ... |
| 4204.831 | CH | 0.520 | −3.360 | −3.360 | −7.699 | ... |
| 4204.858 | Gd II | 0.522 | −0.668 | −0.668 | −6.787 | ... |
| 4204.990 | Cr I | 4.616 | −1.457 | −1.457 | −6.658 | −7.852 |
| 4205.000 | Fe I | 4.220 | −1.900 | −2.150 | −7.000 | −7.548 |
| 4205.038 | V II | 1.686 | −1.850 | −1.875 | −6.800 | −7.913 |
| 4205.042 | Eu II | 0.000 | +0.250 | +0.120 | −6.800 | ... |
| 4205.084 | V II | 2.036 | −1.100 | −1.300 | −6.900 | −7.956 |
| 4205.098 | Fe I | 2.559 | −4.900 | −4.900 | −6.671 | −7.865 |
| 4205.107 | Cr I | 4.532 | −1.160 | −1.160 | −6.582 | −7.776 |
| 4205.163 | Ce II | 1.212 | −0.653 | −0.653 | −6.672 | ... |
| 4205.253 | Nd II | 0.680 | −0.992 | −0.992 | −6.699 | ... |
| 4205.303 | Nb I | 0.049 | −0.850 | −0.850 | −6.677 | ... |
| 4205.381 | Mn II | 1.809 | −3.300 | −3.376 | −6.800 | −8.001 |
| 4205.402 | CH | 0.488 | −2.300 | −3.960 | −8.000 | ... |
| 4205.427 | CH | 1.019 | −2.300 | −1.130 | −8.000 | ... |
| 4205.491 | CH | 1.019 | −3.463 | −3.463 | −8.000 | ... |
| 4205.533 | CH | 1.019 | −1.800 | −1.149 | −8.000 | ... |
| 4205.538 | Fe I | 3.417 | −1.100 | −1.435 | −7.800 | −7.224 |

a All line data except Γ_e from Kurucz databases via VALD (unless otherwise noted).

b Van der Waals parameters where available from Barklem et al. (2000) via VALD (unless otherwise noted).

All molecular line data (except Γ_e, from χ^2 minimization) from Kurucz web site: http://kurucz.harvard.edu/LINELISTS/LINESMOL/.

**TABLE 5**

**LINE LIST FOR THE REGION NEAR EU II AT 6645 Å**

| λ (Å) | Element | Lower level (eV) | log g_f | Solar fit | VALD | Solar fit | VALD |
|-------|---------|-----------------|---------|-----------|------|-----------|------|
| 6644.320 | CN | 0.805 | −1.456 | −2.258 | −7.695 | ... |
| 6644.415 | La I | 0.131 | −1.330 | −2.070 | −8.000 | ... |
| 6645.111 | Eu II | 1.380 | +0.219 | +0.205 | −7.218 | ... |
| 6645.210 | S II | 6.083 | −2.510 | −2.120 | −7.118 | ... |
| 6645.372 | Fe I | 4.386 | −2.759 | −3.536 | −6.780 | −7.808 |

a All line data except Γ_e from Kurucz databases via VALD (unless otherwise noted).

b Van der Waals parameters where available from Barklem et al. (2000) via VALD (unless otherwise noted).

c All molecular line data (except Γ_e, from χ^2 minimization) from Kurucz web site: http://kurucz.harvard.edu/LINELISTS/LINESMOL/.

d Identification and parameters from Kurucz line lists hosted by the University of Hannover: http://www.pmp.uni-hannover.de/cgi-bin/ssi/test/kurucz/sekur.html.

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For each star we calculate a weighted average europium abundance value based on the three (or, in some cases, two) spectral lines. Weighting the average is important because for stars with relatively few observations (e.g., HD 156365 in Fig. 1), the weak line at 6645 Å should be weighted significantly less than the more robust blue lines. Stars with a larger number of observations and higher S/N spectra (e.g., HD 144585 in Fig. 1) should have the 6645 Å line weighted more strongly. In order to determine the relative weights of the three spectral lines, we tested the robustness of our fit by adding artificial noise to the spectra. We describe that process in § 3.3.

3.3. Error Analysis

We begin our error analysis by adding to the data Gaussian-distributed random noise with a standard deviation set by the photon noise at each pixel. We then fit the europium line again, using the same iterative $\chi^2$-minimization process described in § 3.2, and repeat the process 50 times. The standard deviation of the 50 Monte Carlo trials determines the relative weights of the lines in the average listed in Table 2, with lower standard deviation lines (corresponding to a more robust fit) weighted more strongly.

As expected, the results of the Monte Carlo trials show that the larger the photon noise in an observation, the less that line is to be weighted. We derive a linear relation between the Poisson uncertainty of an observation and its relative weight, based on the Monte Carlo results. Because the Monte Carlo trials are CPU intensive, we plan to use that relation to determine relative weights in the future.

We estimate the uncertainty of our europium abundances to be the sum of the squares of the residuals for all three lines, where we assign the residuals the same relative weights we applied when calculating the average. We also impose an error floor of 0.02 dex, added to the uncertainty in quadrature. The error floor comes from a comparison of abundance values from the individual lines (Fig. 6, discussed in more detail in § 4.1); error bars of 0.03 dex on each europium measurement translates into an uncertainty of 0.02 dex for the final averaged value. The 0.02 dex error floor is included in the uncertainty quoted in Table 2.

As an initial test of the robustness of our fitting routine, we measure the europium abundance in a spectrum of Vesta, which serves as a solar proxy. The values are listed in the last row of Table 2. The three Vesta europium abundances have a standard deviation of 0.022 dex, indicating that systematic errors (≅0.03 dex for Vesta, its offset from the solar value) may be a significant portion of the error budget.
For the moment we absorb any systematic error with our random error estimates. The full sample of 1000 stars, the analysis of which will follow this work, will allow a far more thorough investigation of the dependence of our results on various model parameters (\(T_{\text{eff}}\), \(\log g\), etc.) than can be accomplished here. Therefore, we delay a substantive discussion of systematics until we have more europium abundance measurements in hand, though we touch on it again in § 4.1 and § 4.2. It is important to note that since the stars in this analysis are similar to the Sun, and we are treating each star consistently, our results will be internally consistent.

3.4. Notes on Individual Lines

3.4.1. Europium 4129 Å

The europium line at 4129 Å is the result of a resonance transition of Eu II, and is a strong, relatively clean line. It provides the most reliable measurement of europium abundance in a star. Our fit to the Eu II line at 4129 Å in the solar spectrum (described in § 3.1) appears as Figure 2, with the 32 hyperfine components (16 each from \(^{151}\)Eu and \(^{153}\)Eu; Ivans et al. 2006) represented in the Figure 2 inset.

In the course of stellar fitting, the europium abundance is determined from the 4129 Å line in all 41 stars except HD 103095. That star is quite metal poor ([M/H] = −1.16) and cool (\(T_{\text{eff}} = 4950\)), factors that likely contribute to the poor fit in the lines adjacent to the Eu II line of interest (see Fig. 5).

3.4.2. Europium 4205 Å

The Eu II line at 4205 Å is the other fine-structure component of the resonance transition responsible for the line at 4129 Å. Though it is as strong as the Eu II line at 4129 Å, contamination from embedded lines (see Fig. 3) has the potential to make the 4205 Å line less reliable. However, it is useful as a comparison line for the results from the 4129 Å Eu II line. Our solar spectrum fit at 4205 Å appears in Figure 3, with the 30 hyperfine components (15 each from \(^{151}\)Eu and \(^{153}\)Eu; Ivans et al. 2006) in the inset. Despite its blended nature, the fit appears sound in all 41 stars.

3.4.3. Europium 6645 Å

The Eu II line at 6645 Å is weaker than the lines in the blue, but it is also relatively unblended, making it worthwhile to fit wherever possible. Our solar spectrum fit at 6645 Å appears in Figure 4, with the inset plot showing the 30 hyperfine components (15 each from \(^{151}\)Eu and \(^{153}\)Eu; Ivans et al. 2006). In
sorbed by the 0.03 dex error bars assigned to each point (necessary to make reduced-\(\sqrt{\chi^2}\) unity even when comparing the nonsystematic blue lines), we make no attempt to correct this systematic trend here.

Between the relatively low measurement uncertainty needed to achieve reduced-\(\sqrt{\chi^2}\) of unity and the minor systematic trend that only appears in the red, we conclude that the europium abundance values derived from the Eu II lines at 4129 Å, 4205 Å, and 6645 Å are consistent with one another.

4.2. Comparison with Literature Europium Measurements

In Figure 7, we compare our final europium abundance measurements to the literature values. The agreement is quite good. The literature values, plotted with the error bars quoted in the original studies, appear as the abscissa. Our europium values, plotted with the error bars calculated in § 3.3 and listed in Table 2, appear as the ordinate. The solid line represents a 1:1 correlation. Comparing the points to the 1:1 line, reduced-\(\sqrt{\chi^2}\) = 2.78. That value is dominated by HD 103095, the Simmerer et al. 2004 data point with the smallest error bars, and omitting it makes the reduced-\(\sqrt{\chi^2}\) = 1.57.

Adopting the global values (\(T_{\text{eff}}\), [M/H], log \(g\)) used by the comparison studies (instead of the VF05 values) drops the reduced-\(\sqrt{\chi^2}\) to 1.93, indicating that some of the scatter in Figure 7 is from the choice of stellar parameters. We emphasize that the VF05 stellar parameters are reliable; we calculate the reduced-\(\sqrt{\chi^2}\) value using the comparison studies’ values in an attempt to separate how much of the disagreement in Figure 7 is from the europium abundance technique and how much is from the parameters adopted.

Omitting the outlier mentioned at the beginning of this section, we examine the data in Figure 7 to search for systematics in our results relative to the literature values. We consider the effects of a global offset in our europium values and a linear trend with europium abundance, finding that systematic offsets of \(\sim 0.1\) dex and linear trends of \(\sim 40\%\) are needed to make reduced-\(\sqrt{\chi^2}\) climb to 2. We conclude that our error bars have sufficiently characterized our uncertainties.

Overall, we find reduced-\(\sqrt{\chi^2}\) to be dominated by the points at \([\text{Eu/H}] < 0.5\), consistent with our conclusion in § 3.2 that our results are most reliable near solar metallicities, although the larger error bars on the Woolf et al. (1995) points make the correlation very forgiving near \([\text{Eu/H}] = 0\). Our spectra have very high S/N: \(\sim 160\) at 4200 Å in a single observation, enhanced substantially by our co-adding procedure (§ 2.2). The automated SME synthesis treats all stars consistently, an especially important feature for line blends in the crowded blue regions. For these reasons, we believe that our europium abundance technique is accurate and robust and that our smaller error bars are warranted.

We conclude that our abundance measurements are consistent with previous studies, not surprising since most abundance
techniques rely on the same Kurucz stellar atmosphere models. Because the majority of the points in Figure 7 fall near the 1:1 correlation, we also conclude that near $\text{[Eu/H]} = 0$ our errors are $\sim 0.03$ dex, though at $\text{[Eu/H]} < -0.5$, the errors may be as high as 0.1 dex.

5. SUMMARY

We have established that our method for measuring europium in solar-metallicity stars using SME is sound. The resolution and S/N of the Keck HIRES spectra are sufficiently high to fit the Eu II lines in question. The values obtained from the three europium lines are self-consistent, and our final averaged europium values for each of the 41 stars in this study are consistent with the literature values for those stars.

By employing SME to calculate our synthetic spectra, we are self-consistently modeling all the lines in the regions of interest. Any blending from neighboring lines is treated consistently from star to star, adding robustness to our europium determination. Using SME has the added benefit of allowing us to adopt the stellar parameters from the SPOCS catalog. Our automated procedure ensures that all stars are treated consistently.

Having established a new method for measuring stellar europium abundances, we intend to apply our technique to 1000 F, G, and K stars from the Keck CPS survey. Our analysis of europium in these stars will represent the largest and most consistent set of europium measurements in solar-metallicity stars to date, and will provide insight into the question of the $r$-process formation site and the enrichment history of the Galaxy.
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