THE MOST METAL-POOR STARS. I. DISCOVERY, DATA, AND ATMOSPHERIC PARAMETERS
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ABSTRACT
We report the discovery of 34 stars in the Hamburg/ESO Survey for metal-poor stars and the Sloan Digital Sky Survey that have \([\text{Fe/H}] \lesssim -3.0\). Their median and minimum abundances are \([\text{Fe/H}] = -3.1\) and \(-4.1\), respectively, while 10 stars have \([\text{Fe/H}] < -3.5\). High-resolution, high-S/N spectroscopic data – equivalent widths and radial velocities – are presented for these stars, together with an additional four objects previously reported or currently being investigated elsewhere. We have determined the atmospheric parameters, effective temperature \((T_{\text{eff}})\) and surface gravity \((\log g)\), which are critical in the determination of the chemical abundances and the evolutionary status of these stars. Three techniques were used to derive these parameters. Spectrophotometric fits to model atmosphere fluxes were used to derive \(T_{\text{eff}}, \log g\), and an estimate of \(E(B-V); H\alpha, H\beta,\) and \(H\gamma\) profile fitting to model atmosphere results provided the second determination of \(T_{\text{eff}}\) and \(\log g\); and finally, we used an empirical \(T_{\text{eff}}\)-calibrated \(H\delta\) index, for the third, independent \(T_{\text{eff}}\) determination. The three values of \(T_{\text{eff}}\) are in good agreement, although the profile fitting may yield systematically cooler \(T_{\text{eff}}\) values, by \(~100\). This collective data set will be analyzed in future papers in the present series to utilize the most metal-poor stars as probes of conditions in the early Universe.

Subject headings: Cosmology: Early Universe, Galaxy: Formation, Galaxy: Halo, Stars: Abundances, Stars: Fundamental Parameters

1. INTRODUCTION
Six decades after the discovery of metal-poor stars by Chamberlain & Aller (1951), the study of these objects has become a major area of research. In 2010, high-resolution, high-signal-to-noise \((S/N)\) chemical abundance analyses existed for some 400 stars that have \([\text{Fe/H}] < -2.5\), some 24 with \([\text{Fe/H}] < -3.5\), and three having \([\text{Fe/H}] < -4.5\) (see the compilation of Frebel (2010)). As discussed by many authors, the most metal-poor stars, believed to have formed at redshifts \(z \gtrsim 6\), are among the best probes of conditions in the early Universe, including in particular the formation of the first stars and the first chemical elements. We shall not repeat here the case for this endeavor, but refer the reader to earlier works (e.g., Bessell & Norris 1984; McWilliam et al. 1995).

1 This paper includes data obtained with the ANU 2.3 m Telescope at Siding Spring Observatory, Australia; the Magellan Clay Telescope at Las Campanas Observatory, Chile; the Keck I Telescope at the W. M. Keck Observatory, Hawaii, USA; and the VLT (Kueyen) of the European Southern Observatory, Paranal, Chile (proposal 281.D-5015).
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10 https://www.cfa.harvard.edu/~afrebel/

11 \([X/Fe] = \log_{10}(N_X/N_{Fe}) \pm \log_{10}(N_X/N_{Fe})\).
2. DISCOVERY AND SELECTION OF PROGRAM STARS

The present program represents the completion of a search over some 30 years for the most metal-poor stars undertaken at the Mount Stromlo & Siding Spring Observatories, ANU (now known as RSAA, ANU), based on techniques involving (in the main part) high-proper-motion stars (the NLTT survey [Luyten 1979, 1980] and metal-weak candidates obtained from Schmidt wide-field objective-prism surveys (the HK Survey [Beers et al. 1985; Beers et al. 1992]) and the Hamburg/ESO Survey (HES [Christlieb et al. 2008]).

Results based at least in part on these efforts have already been presented by Aoki et al. (2002, 2006), Bessell & Norris (1984), Cayrel et al. (2004), Christlieb et al. (2002, 2004), Frebel et al. (2005, 2004, 2007a, b), Honda et al. (2004), Li et al. (2010), Norris et al. (1995, 1999, 2001, 2007), Ryan & Norris (1991), Ryan et al. (1991, 1996), and Schöck et al. (2009). These include the discovery and analysis of three of the four most metal-poor stars currently known: HE 0107–5240 with [Fe/H] = –5.3 (Christlieb et al. 2002, 2004), HE 1327–2326 with [Fe/H] = –5.4 (Frebel et al. 2005, Aoki et al. 2006), and HE 0557–4840 with [Fe/H] = –4.8 (Norris et al. 2007).

The current sample of the most metal-poor stars is based principally on a medium-resolution spectroscopic survey of metal-poor candidates from the HES, supplemented by a few stars known to be extremely metal-poor from other sources.

2.1. Medium-resolution Spectroscopy with the ANU 2.3 m Telescope

Metal-poor candidates from the Hamburg/ESO objective-prism surveys have been observed during the present investigation with the Australian National University’s 2.3 m Telescope/Double Beam Spectrograph combination on Siding Spring Mountain, during observing sessions in 2005–2009. The spectra have a resolving power R ~ 1600, and cover the wavelength range 3600–5400 Å. They were reduced with the FIGARO package and flatfielded and wavelength calibrated by using spectra of quartz and Fe-Ar lamps, respectively. Following Beers et al. (1994, their Table 2), we measured the Ca II K line index, K′, the CH G-band index, G′, and the hydrogen indices Hγ and Hδ to form H′, the mean of the two estimates. (H′ was not measured for objects with G′ > 4.0 Å, for which the index is affected by strong CH absorption). We used these data, following the precepts of Beers et al., to obtain estimates of iron abundance, here designated [Fe/H]K. Analysis of some of these spectra have also been used for discussion of the MDF of the Galactic halo by Schöck et al. (2009) and Li et al. (2010), to which we refer the reader. For the present work, we recall that we were interested in discovering stars with [Fe/H]K ≤ –3.0, and have adopted techniques that differ in two respects from those works. First, our investigation used the original abundance calibration of Beers et al. (1994). Second, that technique requires values not only of K′ but also of (B–V)0. For (B–V)0 ≤ 0.70 we used the hydrogen index, when available, to provide the color estimate \(B–V)_{0} = 0.840 – 0.1541H′ + 0.01148Hδ^2\); otherwise, we used \((B–V)_{HES}\) from the HES survey (Christlieb et al. 2008), corrected for reddening following Schlegel et al. (1998).

In what follows we present data for stars that were discovered to have [Fe/H]K ≤ –3.0, based on the above medium-resolution spectroscopy obtained in 2005–2008. Results for some extremely metal-poor stars that were observed in 2005 (e.g., HE 0557–4840, [Fe/H] = –4.8) have already been published (Norris et al. 2007) or are the subject of analysis currently underway (García Pérez et al. 2008). Followup investigation of objects observed in 2009 is work for the future.

During 2005–2009 we obtained some 3400 spectra of HES metal-poor candidates with the 2.3 m Telescope, and from those observed in 2005–2008 selected the 1460 stars that satisfy the following criteria: (1) B magnitudes in the range 12.6 < B_HES ≤ 16.5; (2) H′, the mean of the Beers et al. (1999) hydrogen Hγ and Hδ indices, less than 5.5 Å (i.e. \((B–V)_{0} ≥ 0.34\)) and \((B–V)_{HES} ≥ 0.30\); (3) photon counts at 4100 Å greater than 200 per ~1 Å pixel; and (4) spectra exhibit no anomalies such as hydrogen or Ca II emission. The first criterion was chosen to discover metal-poor stars that could be observed with 6–10 m class telescopes to obtain spectra at high resolution and high-S/N in times less than a few hours; the second confines the selection almost exclusively to main-sequence dwarfs, and to red giant branch (RGB) and red horizontal branch (RHB) stars; and the third accepts medium-resolution spectra with sufficient S/N to produce abundance accuracy of \(\Delta [Fe/H] \sim 0.2–0.3\) dex – at least for stars that are not carbon-rich (and for which abundances from medium-resolution spectroscopy are less well-determined). For the 24 HES dwarfs and giants in the present sample, the CH G-band index \(G′ < 1.5\) Å, the dispersion of the differences between the present values of [Fe/H]K and those we obtain from the analysis of our high-resolution, high-S/N, spectra is 0.30 dex, while for the remaining seven (carbon-rich) objects, which have \(G′ > 3.5\) Å, the dispersion of the abundance differences is 0.40 dex.

In Figure I we present stars having [Fe/H]K < –2.5 in the \(G′\) (carbon-sensitive index) vs. [Fe/H]K plane, where the top panel contains objects with \((B–V)_{0} > 0.55\) (principally giants) and the middle panel shows those with \((B–V)_{0} < 0.55\) (principally dwarfs). The sloping lines in the two panels are arbitrarily chosen to separate potentially carbon-normal and carbon-rich objects, while the vertical lines are included to emphasize the region of immediate interest for the present investigation – [Fe/H]K < –3.0. More metal-poor than this limit our 2.3m sample survey contains 109 stars. In Figure I we identify those objects with [Fe/H]K ≤ –3.0 for which high-resolution, high-S/N data have been obtained in the present work, together with those of Norris et al. (2007) and García Pérez et al. (2008), as filled star symbols. Open circles represent stars for which high-resolution data are not yet available.

The bottom panel in Figure I presents the MDF of all of the stars in the upper two panels, where the upper thick line represents the distribution for the complete sample of stars from the 2.3 m HES sample described above, and the lower thick line shows that of only the stars having high-resolution data. The thin, mostly horizontal line in the figure shows the completeness function from Schöck et al. (2009) and Li et al. (2010) for the detection of metal-poor stars in medium-resolution investigations of the HES: below [Fe/H] = –3.0, the HES is essentially complete. Consideration of the thick lines in the figure shows quite clearly the strong bias we have introduced for details of the fourth star, SDSS J102915+172927, see Caffau et al (2011).

12 For details of the fourth star, SDSS J102915+172927, see Caffau et al (2011).
13 http://www.aao.gov.au/figaro
14 Based on colors and reddenings of high-proper-motion stars presented by Carney et al. (1993), together with values of \(K′\) obtained with the equipment described above as part of another investigation.
into the completeness function by our emphasis on observing the most metal-poor stars. We shall bear this in mind in subsequent discussions of the MDF at the lowest metallicities.

2.2. Supplementary Selection

We augmented our program sample by the inclusion of eight stars from other sources. These comprise four stars from the Sloan Digital Sky Survey (SDSS: York et al. 2000), three dwarfs (BS 16545-089 and HE 1346–0427 from Cohen et al. 2004, and HE 0945–1435 from García Pérez et al. 2008), and the red giant CS 30336-049 (Tanner et al. 2006; Lai et al. 2008).

2.3. The Sample

Our total sample thus comprises 38 stars – 30 from the 2.3m survey described in Section 2.1, four from the SDSS, BS 16545-089 and CS 30336-049 for the HK survey, and HE 0945–1435 and HE 1346–0427 from the HES. The basis data for these stars are presented in Table 1. Columns (1)–(3) contain the star names and coordinates, columns (4)–(6) contain B_{HES}, (B−V)_0, and the source of the color, and columns (7)–(10) present K′, G′, H′, and [Fe/H]_K, respectively. (We note that the first four entries in the table are based on spectra taken from the SDSS archives.) For completeness and comparison purposes, column (11) presents values of [Fe/H] from Paper II, which result from the model atmosphere analysis of the high-resolution, high-S/N spectra presented here. Of these stars, 34 are original to the present work.

3. HIGH RESOLUTION SPECTROSCOPY

3.1. Magellan, Keck, and VLT Spectra

High-resolution, high-S/N spectra of the 38 program stars in Table 1 were obtained with the Magellan/MIKE, the Keck/HIRES, and VLT/UVES telescope/spectrograph combinations during 2007–2008. Details of the observing sessions and instrumental set-ups are presented in Table 2 where columns (1)–(4) present the telescope/spectrograph combinations, observing dates, wavelength ranges, and resolving powers (R = \lambda/\Delta \lambda), respectively.

The Magellan and Keck observations were obtained in Visitor Mode, during which data were also obtained of “standard” metal-poor stars for comparison purposes, together with quartz-iodine and ThAr lamps for flat-fielding and wavelength calibration. We tailored data acquisition for the program stars to obtain S/N ~ 100 per pixel at 4500 Å for the most metal-poor stars in our sample. To do this we began our observations of each star in “snapshot” mode with a minimal number (~1–3) of 1800 sec exposures, which we reduced in real time to permit us, by comparison with our library of high-resolution extremely metal-poor stars, to give priority to the more metal-poor objects.

We then obtained additional exposures as necessary to yield higher S/N for the most interesting objects. The reader will see this reflected to some extent in the S/N values reported below. The data were processed with standard IRAF\(^1\) procedures (supplemented by the cosmic-ray removal algorithm of Pych 2004) to obtain flat-fielded, wavelength-calibrated, cosmic-ray-corrected, co-added, and continuum-normalized spectra (see, e.g., Yong et al. 2003a).

\(^1\) IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
Four exposures were obtained for HE 1506–0113 in Service Mode with the VLT/UVES system, each having an integration time of 2500 sec, with spectrograph settings as used in our investigation of HE 0557–4840 (Norris et al. 2007). These four ESO pipeline-reduced spectra were co-added to produce the final spectrum, which was then continuum normalized.

Examples of the high-resolution spectra are presented in the lower panels of Figure 2, which cover the wavelength range 3900–4000 Å, together in the upper panels with the corresponding medium-resolution spectra (3800–4600 Å) described in Section 2.1. The $S/N$ (per 0.017 Å pixel at 4500 Å) of the final high-resolution spectra are presented in the first row of each of Tables 3–6. The range in $S/N$ for the total sample is 23–210, with median 61, while for stars with high-resolution abundances [Fe/H] < −3.5 the median $S/N$ is 118. For the latter group, we note for the record that the mean $B$ magnitude is 15.3.

### Table 1

| Star            | RA (2000) | Dec (2000) | $R_{HES}$ | $(B-V)_0$ | $S^a$ | $K'/(\AA)$ | $G'/(\AA)$ | $H'/(\AA)$ | [Fe/H]_K | [Fe/H] |
|-----------------|-----------|------------|-----------|-----------|-------|------------|------------|------------|---------|--------|
| HE 0557–4840    | 05 57 13.5 | −48 40 13  | 4.30      | 3.50      | 2.60  | 3.40       | 2.40       | 3.20       | −3.40   | −3.40  |
| HE 0634−6000    | 06 34 39.1 | −60 00 15  | 5.00      | 4.80      | 3.80  | 3.60       | 3.40       | 3.20       | −3.50   | −3.50  |
| HE 0701−3000    | 07 01 23.5 | −30 00 15  | 5.50      | 5.30      | 4.40  | 4.20       | 4.00       | 3.80       | −3.60   | −3.60  |
| HE 0732−3000    | 07 32 45.1 | −30 00 15  | 6.00      | 5.80      | 4.90  | 4.70       | 4.50       | 4.30       | −3.70   | −3.70  |

3.2. Equivalent Widths

Equivalent widths have been measured from these spectra as described in Norris et al. (2010a), to whom we refer the reader for details. As noted above, we begin with the line list of Cavrel et al. (2004), which we supplement here with lines of Sr II and Ba II. We also recall that the spectra of carbon-rich stars can be heavily contaminated by CH lines. To minimize this effect we followed the spectrum synthesis technique of Norris et al. (2010b) to determine when the blending of CH lines with atomic features would contaminate the latter. For stars having $G' > 3.5$ Å, we did not measure atomic features susceptible to such contamination. We also excluded lines in regions with observed C$_2$ absorption in these objects.

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*a* Source of $(B-V)_0$: 1 = $S^*$, see Section 2.1; 2 = Cohen et al. (2003); 3 = Norris et al. (2009); 4 = $(B-V)_{HES}$, see Section 2.2

*b* SDSS “MJD-plug plate-fiber” nomenclature

*c* $B$ from SDSS (rows (1)–(4)); (Cohen et al. 2008) (row 5), adopting color from this table; and Norris et al. (2009) (row 6)

*d* Average of dwarf and subgiant values of [Fe/H] from Table 1 of Paper II
### Table 2: Log of High-Resolution Spectroscopic Observations

| Telescope/ Spectrograph | Date          | Wavelength range (Å) | Resolving power |
|-------------------------|---------------|-----------------------|-----------------|
| Magellan/MIKE           | 2007 Jun 20–23 | 3300–4900             | 39000           |
|                         |               | 4900–9400             | 31000           |
|                         | 2007 Dec 21–22| 3300–4900             | 37000           |
|                         |               | 4900–9400             | 30000           |
|                         | 2008 Sep 6–7  | 3300–4900             | 36000           |
|                         |               | 4900–9400             | 30000           |
| Keck/HIRES              | 2007 Nov 30 – Dec 1 | 3720–4600             | 48000           |
|                         |               | 4660–5600             | 48000           |
|                         |               | 4020–4660             | 49000           |
|                         | 2008 Mar 25–28| 4750–6190             | 49000           |
|                         |               | 6340–7760             | 49000           |
| VLT/UVES                | 2008 Jul 3–24 | 3300–4520             | 40000           |
|                         | (2.7 hrs Service Observing) | 4790–5750             | 40000           |
|                         |               | 5840–6800             | 40000           |

### Table 3: Atomic Data and Equivalent Widths (Å) for Program Stars

| Wavelength (Å) | Species | $\chi$ (eV) | log $g_f$ | HE 0146 | HE 0207 | HE 0228 | HE 0231 | HE 0253 | HE 0314 | HE 0355 | HE 0945 | HE 1055 | HE 1116 |
|---------------|---------|-------------|-----------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| 5889.95       | 11.0    | 0.00       | 0.11      | 183.0   | ...     | ...     | ...     | 20.2    | 70.4    | 10.6    | 156.0   | ...     |
| 5895.92       | 11.0    | 0.00       | -0.19     | 105.0   | 17.8    | 10.9    | ...     | 11.6    | 50.6    | 12.6    | 129.0   | 32.7    |
| 3829.36       | 12.0    | 2.71       | -0.21     | 93.0    | 65.4    | ...     | 88.7    | ...     | 93.6    | 43.8    | 86.1    | 78.5    |
| 3832.30       | 12.0    | 2.71       | 0.15      | ...     | ...     | ...     | ...     | ...     | 106.5   | ...     | 106.5   | ...     |
| 3838.29       | 12.0    | 2.72       | 0.41      | ...     | ...     | ...     | ...     | ...     | 117.5   | ...     | 109.5   | ...     |

### Table 4: Atomic Data and Equivalent Widths (Å) for Program Stars

| Wavelength (Å) | Species | $\chi$ (eV) | log $g_f$ | HE 0146 | HE 0207 | HE 0228 | HE 0231 | HE 0253 | HE 0314 | HE 0355 | HE 0945 | HE 1055 | HE 1116 |
|---------------|---------|-------------|-----------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| 5889.95       | 11.0    | 0.00       | 0.11      | 186.0   | 138.5   | ...     | 44.2    | 45.1    | 29.9    | ...     | ...     | 67.1    | 16.4    |
| 5895.92       | 11.0    | 0.00       | -0.19     | 154.5   | 23.4    | ...     | 37.7    | 23.1    | ...     | ...     | ...     | 39.6    | 10.6    |
| 3829.36       | 12.0    | 2.71       | -0.21     | ...     | ...     | 43.2    | 100.2   | 88.8    | 78.4    | ...     | ...     | 98.1    | 55.0    |
| 3832.30       | 12.0    | 2.71       | 0.15      | ...     | ...     | ...     | ...     | ...     | ...     | ...     | ...     | ...     |
| 3838.29       | 12.0    | 2.72       | 0.41      | ...     | ...     | ...     | ...     | ...     | ...     | ...     | ...     | ...     |
### TABLE 5

ATOMIC DATA AND EQUIVALENT WIDTHS (\(\text{mÅ}\)) FOR PROGRAM STARS

| Wavelength (Å) | Species \(\chi\) | \(\log g\) | HE 1142 (Å) | HE 1201 (Å) | HE 1204 (Å) | HE 1207 (Å) | HE 1320 (Å) | HE 1346 (Å) | HE 1402 (Å) | HE 1506 (Å) | HE 2020 (Å) | HE 2032 (Å) |
|----------------|-------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| 5889.95        | 11.0              | 0.00        | 0.11        | 87.9        | 17.7        | 67.8        | 156.0       | 79.5        | 19.8        | 29.7        | 185.0       | 23.5        |
| 5895.92        | 11.0              | 0.00        | -0.19       | 53.7        | 8.5         | ...         | 105.0       | 55.8        | 13.7        | 25.9        | 152.0       | 9.9         |
| 3829.36        | 12.0              | 2.71        | -0.21       | 139.5       | 60.7        | ...         | 101.8       | 100.7       | ...         | 86.7        | 138.0       | 85.5        |
| 3832.30        | 12.0              | 2.71        | 0.15        | ...         | ...         | ...         | 128.5       | 123.0       | ...         | ...         | 116.5       | ...         |
| 3838.29        | 12.0              | 2.72        | 0.41        | ...         | ...         | ...         | 143.0       | 136.5       | ...         | ...         | 121.5       | ...         |

S/N\(^a\)

W(min) (mÅ) 15 5 16 10 10 5 8 5 13 10

**REFERENCES.** — Note: Table 5 is published in its entirety in the electronic edition of The Astrophysical Journal. A portion is shown here for guidance regarding its form and content.

\(^a\) S/N per ∼0.17 Å pixel at 4500 Å

\(^b\) These lines produce discrepant abundances and are not included in the results reported in Paper II

### TABLE 6

ATOMIC DATA AND EQUIVALENT WIDTHS (\(\text{mÅ}\)) FOR PROGRAM STARS

| Wavelength (Å) | Species \(\chi\) | \(\log g\) | HE 2047 (Å) | HE 2135 (Å) | HE 2136 (Å) | HE 2139 (Å) | HE 2141 (Å) | HE 2142 (Å) | HE 2202 (Å) | HE 2246 (Å) | HE 2247 (Å) |
|----------------|-------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| 5889.95        | 11.0              | 0.00        | 0.11        | 44.2        | 17.6        | 38.7        | 146.0       | 45.2        | 187.0       | ...         | 142.0       |
| 5895.92        | 11.0              | 0.00        | -0.19       | 22.2        | 36.2        | 24.9        | 130.0       | 26.5        | 166.5       | 192.5       | 120.0       |
| 3829.36        | 12.0              | 2.71        | -0.21       | 68.7        | 57.5        | 70.6        | 136.0       | 88.3        | 166.5       | ...         | 85.3        |
| 3832.30        | 12.0              | 2.71        | 0.15        | ...         | ...         | 120.0       | ...         | ...         | ...         | ...         | ...         |
| 3838.29        | 12.0              | 2.72        | 0.41        | ...         | ...         | 119.0       | ...         | ...         | ...         | ...         | ...         |

S/N\(^a\)

W(min) (mÅ) 10 7 15 8 10 15 15 8 20

**REFERENCES.** — Note: Table 6 is published in its entirety in the electronic edition of The Astrophysical Journal. A portion is shown here for guidance regarding its form and content.

\(^a\) S/N per ∼0.17 Å pixel at 4500 Å

\(^b\) These lines produce discrepant abundances and are not included in the results reported in Paper II
each of the spectra, which we present in the second row of
Figure 3(a). For the 37 objects, the median RMS scatter
is 2.7 mÅ. We also estimated the line strengths for 14 elements in the wavelength range
3850–4000 Å. Columns (1)–(4) contain line identification, lower excitation potential (χ), and log gf value, respectively, for 191 unblended lines suitable for model atmosphere abundance analysis, taken from Cayrel et al. (2004) Table 3), together with values from the literature for Sr II and Ba I 

The remainder of the table is populated by equivalent widths. Some of the lines lead to significantly discrepant abundances compared with those obtained from other lines of the same species. We flag these values in Tables 3–6 and have excluded them from the analysis in Paper II.

We have compared our results with those of other workers. Figure 3(b) and (c) compare the present equivalent widths with those of Lai et al. (2008) (CS 30336-049) and Cohen et al. (2004) (HE 1346–0427), for which the RMS scatters are 3.0 and 4.4 mÅ, respectively. We have also obtained data for well-observed stars in the present program and found good agreement with the results of others. As an example, Figure 3(d) compares our equivalent widths with those of Cayrel et al. (2004) for CD−38°245, where the RMS scatter is 2.4 mÅ.

3.3. Radial Velocities

Radial velocities were measured from the high-resolution spectra (for all but one program star, HE 1506–0113) using the FXCOR task in IRAF. We cross-correlated individual spectra with a template spectrum obtained with the same set-up on the same observing run (generally a high-S/N exposure of a metal-poor standard). Given the weakness of lines in these extremely metal-poor stars, only a limited number of orders provided useful information. In these orders, the peak of the cross-correlation function was fit with a Gaussian. The velocities from multiple orders were averaged to obtain our final radial velocities for each individual spectrum with a typical uncertainty of 0.5 km s−1, but with values as high as 3 km s−1. For HE 1506−0113 the velocity was determined from the four individual VLT spectra discussed in Section 3.1 by cross-correlating them with a model atmosphere synthetic spectrum as described by Norris et al. (2010b, Section 2.4).

Table 7 presents average heliocentric velocities obtained on each of our observing runs, together in Table 8 with velocities and the epoch of observation for each individual observation.

4. TEMPERATURE AND GRAVITY DETERMINATIONS

In order to determine the stellar atmospheric parameters necessary for our subsequent chemical abundance analysis we have adopted three independent techniques. First, we employed the fitting of model atmosphere fluxes to spectrophotometric observations. In principal, this provides unique values of the Teff, log g, and metallicity [M/H], although uncertain.
Fig. 3.—Comparison of equivalent widths (a) measured in the present work by J. E. N. and D. Y., and (b)–(d) between the present work and that of (Lai et al. 2008), (Cohen et al. 2004), and (Cayrel et al. 2004).

### Table 7: Radial Velocities

| Star            | Telescope/Date | V\(^b\) (km s\(^{-1}\)) | s.e.\(^b\) (km s\(^{-1}\)) |
|-----------------|----------------|--------------------------|-----------------------------|
| 52972-1213-507  | K Nov07        | -177.0                   | 0.5                         |
| 53327-2044-515  | K Nov07        | -193.5                   | 0.5                         |
| 53436-1996-093  | K Nov07        | -15.3                    | 1.7                         |
| 54142-2667-094  | K Nov07        | 43.4                     | 0.7                         |
| BS 16545-089    | K Mar08        | -161.1                   | 0.1                         |
| CS 30336-049    | M Jun07        | -236.6                   | 0.8                         |
| HE 0049–3948    | M Dec07        | 190.8                    | 0.5                         |
| HE 0057–5959    | M Sep08        | 190.6                    | 0.9                         |
| HE 0102–1213    | K Nov07        | 90.5                     | 0.5                         |
| HE 0146–1548    | K Nov07        | -114.9                   | 0.5                         |
| HE 0207–1423    | K Nov07        | -209.6                   | 0.5                         |
| HE 0226-4047    | M Dec07        | 123.8                    | 0.6                         |
| HE 0231–6025    | M Dec07        | 296.6                    | 0.5                         |
| HE 0253–1331    | K Nov07        | 25.2                     | 0.5                         |
| HE 0314–1739    | K Nov07        | 40.9                     | 0.5                         |
| HE 0355–3728    | M Dec07        | 82.0                     | 1.8                         |
| HE 0945–1435    | K Mar08        | 121.8                    | 0.5                         |
| HE 1055+0104    | K Nov07        | 324.6                    | 0.5                         |
| HE 1116–0054    | M Jun07        | 149.1                    | 0.7                         |
| HE 1142–1422    | M Jun07        | 102.3                    | 0.5                         |
| HE 1201–1312    | M Jun07        | 238.8                    | 0.5                         |
| HE 1204–0744    | M Jun07        | 237.2                    | 0.5                         |
| HE 1207–3108    | M Jun07        | -49.7                    | 2.7                         |
| HE 1320–2952    | M Jun07        | -3.7                     | 0.5                         |
| HE 1346–0427    | K Mar08        | 390.0                    | 0.5                         |
| HE 1346–0427    | K Mar08        | 390.0                    | 0.9                         |
| HE 1402–0523    | M Jun07        | -68.8                    | 0.5                         |
| HE 1506–0113    | V Jul08        | -137.1                   | 0.3                         |
| HE 2032–5633    | M Jun07        | -41.5                    | 2.2                         |
| HE 2032–5633    | M Jun07        | 260.5                    | 0.5                         |
| HE 2047–5612    | M Jun07        | -50.0                    | 1.6                         |
| HE 2135–1924    | K Nov07        | -252.9                   | 1.6                         |
| HE 2136–6030    | M Jun07        | 156.5                    | 2.8                         |
| HE 2139–5432    | M Dec07        | 113.4                    | 0.7                         |
| HE 2247–7400    | M Jun07        | 115.5                    | 0.5                         |
| HE 2247–7400    | M Jun07        | 115.5                    | 0.5                         |
| HE 2247–7400    | M Jun07        | 115.5                    | 0.5                         |

\(^{a}\) K = Keck, M = Magellan, V = VLT

\(^{b}\) Heliocentric radial velocity and standard error of the mean

Ties in interstellar reddening, flux calibration, and model atmosphere fluxes can influence the fits. The metallicity determined from the global flux is the least precisely determined parameter, but the imprecision little affects fitting the other two parameters. Interstellar reddening is very important, because it affects the fitted value of both \(T_{\text{eff}}\) and \(\log g\). In some cases, the reddening can be fitted together with the stellar parameters, by comparing the size of the residuals between the different reddening-corrected observations and the fitted fluxes. In other cases, its value can be achieved by examining the variation of the residuals with wavelength. Theoretical isochrones for halo stars can also be used to constrain combinations of \(T_{\text{eff}}\), \(\log g\), \([M/H]\), and \(E(B-V)\).

A second important determinant of \(T_{\text{eff}}\) is the hydrogen line profiles, in particular those of \(\text{H}\alpha\), \(\text{H}\beta\), and \(\text{H}\gamma\). For \(T_{\text{eff}} < 7000\) K, the hydrogen line profile wings are only
slightly sensitive to log g, but given an estimate of the appropriate log g from the flux fitting, an excellent reddening-independent temperature can be derived (e.g., Fuhrmann et al. 1993; Barklem et al. 2002; Asplund et al. 2006; Barklem 2008). Care must be taken to ensure that the continuum of the echelle spectra over the hydrogen lines is correctly defined, but this can be done reliably using a smooth-spectrum star or the shape of the continuum in neighbouring orders. The treatment of convection in the 1D model atmospheres does alter the hydrogen line profiles (e.g., Fuhrmann et al. 1993; Barklem et al. 2002; Heiter et al. 2002; Barklem 2008), but these differences are minimal for Hα. More recently, the effects on hydrogen lines of 3D hydrodynamical model atmospheres in self-consistently-computed convective energy transport has been explored (e.g., Ludwig et al. 2009), but a systematic study of the observed spectra of 3D models still remains to be done. In the present work we have adopted the 1D formalism, and intend to return to this important issue in a later study.

Finally, we also used an Hδ line index (HP2) measured from medium-dispersion spectra and calibrated as a function of \( T_{\text{eff}} \) for a large sample of stars (see Appendix). This is a very useful technique, as it is independent of reddening, and can be used when a flux-calibrated spectrum is unavailable.

We discuss each of these in turn.

### 4.1. Spectrophotometry

The flux spectrum of a star can be considered as reflecting the underlying blackbody temperature, moderated by the photospheric opacity sources. In the UV-optical region for A–K stars, there are two main continuum opacity sources: bound-free neutral hydrogen (b-f HI) and the bound-free negative hydrogen ion (photoelectric ionization) (b-f H\(^-\)) (see, e.g., Gray 1992). In the UV below 3646 Å, absorption from HI atoms in level \( n = 2 \) produces the Balmer continuum. In the optical between 3646 Å and 8206 Å, absorption from HI atoms in level \( n = 3 \) produces the Paschen continuum. Plotted against wavelength, the shape of the b-f HI opacity is a series of ramps that terminate abruptly at wavelengths corresponding to the different excitation levels of the hydrogen atom. In contrast, the b-f H\(^-\) opacity is smooth and approximately bell-shaped (FWHM 10,000 Å), with maximum absorption at about 8500 Å. The b-f HI opacity dominates in A stars, while H\(^-\) dominates for temperatures cooler than the Sun. As the ratio of the number of H\(^-\) to HI is proportional to the electron pressure (or effective gravity), higher gravity increases the contribution of the H\(^-\) opacity relative to that from HI.

Figure 4 shows the spectra of three MARCS models with the same \( T_{\text{eff}} = 6000 \text{K} \) and metallicity [Fe/H] = −2.5 but different values of log g corresponding to the main sequence, subgiant branch, and horizontal branch for halo stars. Note not only the different Balmer Jumps, but the different slopes redward of the Balmer Jump.

In fitting the flux spectrum of an F–K star, one should note that the temperature is determined mainly from the slope of the Paschen continuum; however, the strength of the hydrogen lines, which are mainly sensitive to temperature in this spectral-type range, can serve as valuable consistency checks on the adopted reddening and the Paschen continuum slope fit. At medium resolution, the metallicity can also be estimated from individual strong lines, such as Ca II and Mg I, as well as from general metal-line blanketing in the violet, and from the strength of molecular bands, such as CH (for carbon-normal stars), MgH, and TiO. How well all these features are fitted is quantitatively evaluated to determine the spectrophotometrically-derived \( T_{\text{eff}}, \log g, [\text{M/H}], \) and \( E(B-V) \). The precision of the spectrophotometrically-derived metallicity differs with \( T_{\text{eff}} \), being higher for K stars than for F stars, but in our experience is normally within \( \pm 0.2 \) dex of the high-resolution spectroscopic estimate. This is more than adequate for discovery programs and for determining \( T_{\text{eff}} \) and log g values.

#### 4.1.1. Spectrophotometric Observations

Medium-resolution spectra of our program stars were taken with the ANU’s 2.3m Telescope on Siding Spring Mountain, primarily with the Double Beam Spectrograph (DBS) at 4 Å resolution, together with some at 2 Å resolution with the Wide-Field Integral Field Spectrograph (WiFeS). Both are double-beam spectrographs that use a dichroic mirror to sepa-

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**TABLE 8**

| Star   | Telescope/Date | Julian Date | \( V_b^{b} \) (km s\(^{-1}\)) |
|--------|----------------|-------------|-------------------------------|
| 52972-1213-507 | K Nov07 | 2454437.06233 | −176.6 |
| 53327-2044-515 | K Nov07 | 2454437.07710 | −177.3 |
| 54346-1996-093 | K Nov07 | 2454437.09230 | −11.0 |

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Figure 4.— The spectrum of three MARCS models with the same \( T_{\text{eff}} = 6000 \text{K} \) and metallicity [Fe/H] = −2.5 but different values of log g corresponding to the main sequence, subgiant branch, and horizontal branch for halo stars. Note not only the different Balmer Jumps, but the different slopes redward of the Balmer Jump.
rate the blue (3000–6200 Å) and red (6000–9700 Å) regions. The spectra were taken using a 2 arcsec slit, with the spectrograph orientation set so the atmospheric dispersion was along the slit. Spectrophotometric standard stars were also observed each night, together with a smooth-spectrum star to enable the removal of telluric features (e.g., Bessell 1999). We used an updated list of standards\footnote{http://www.mso.anu.edu.au/~bessell/FTP/Spectrophotometry/} that were selected from the Next Generation Spectral Library (NGSL) \cite{Heap:2007}\footnote{http://archive.stsci.edu/prepds/stisngsl/index.html}. The CCD frames were bias subtracted and flat fielded, the cosmic rays removed, the star and sky spectra extracted, and the sky removed. All spectra were divided by the extracted spectrum of a smooth-spectrum star (generally EG131 or L745-46a, cool He white dwarfs) to remove the effects of the grating and CCD response, and in the red, any telluric absorption, resulting in a gently curved spectrum. The spectra were then wavelength fitted, wavelength scrambled (rebinned to a linear scale), and corrected for the continuous atmospheric extinction appropriate for their observed airmass. The standard-star spectra (generally 8–10 per night) were compared with their standard values, and the mean spectrophotometric calibration determined and applied to all the program stars.

4.1.2. Model Atmosphere Fluxes

We initially used the Munari et al. \cite{Munari:2005}\footnote{http://marcs.astro.uu.se} library of synthetic spectra at 1 Å resolution, but have recently added the LTE model atmosphere fluxes from the MARCS grid \cite{Gustafsson:2008}\footnote{http://archives.eso.org/ftp/pub/data/spectroscopy/index.html}. The MARCS spectra are not line-by-line computed spectra (as are the Munari et al. spectra), but are fluxes generated using statistically sampled opacities; however, smoothed to 4 Å resolution they are very good representations of real spectra. Although restricted to temperatures below 8000 K, the MARCS model atmosphere grid covers all the parameter space of the halo stars that we are interested in.

The Munari et al. \cite{Munari:2005} spectra cover a wide range of atmospheric parameters: $3500 < T_{\text{eff}} < 47500$ K, $0.0 < \log g < 5.0$, and $-2.5 < [\text{M/H}] < +0.5$. Extension of the full grid to lower metallicity is underway by R. Sordo (2010, private communication), but many relevant lower metallicity models are already available\footnote{http://marcs.astro.uu.se}.

For the MARCS spectra, the stellar atmospheric model parameters ranged in $T_{\text{eff}}$ from 2500 K to 8000 K, in steps of 100 K from 2500 K to 4000 K, and in steps of 250 K between 4000 K and 8000 K. The log g values were between 1.0 and 5.5 in steps of 0.5. Overall logarithmic metallicities relative to the Sun were between $-5.0$ and $+1.0$ in variable steps. The reference solar abundance mixture was that of Grevesse et al. \cite{Grevesse:2007}. Plane-parallel models were used for geometries between 3.0 and 5.0, and spherical models (1M$_\odot$) for lower gravities. For the lower-metallicity stars, alpha-enhanced models were used: [$\alpha$/Fe] = +0.25, for $-0.5 \leq [\text{Fe/H}] \leq -1.5$, and +0.50, for $-1.5 < [\text{Fe/H}] \leq -5.0$.

4.1.3. Spectrophotometric Flux Fitting Method

A python\footnote{http://www.python.org/psf}\ program, fitter, written by S. J. M., was used for the fitting. This will be described in greater detail in a later pa-

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However, Barklem (2008) notes the role of possible departures from LTE, differences between 1D and 3D model atmospheres, and the effects that the value of the mixing-length parameter has on the Balmer-line profiles.

The $T_{\text{eff}}$ were derived by P.S.B. from fitting the H$_\alpha$, H$_\beta$, and H$_\gamma$ profiles measured from our echelle spectra, described in Section 3.1. The method employed for merging of spectral orders and continuum normalisation of the spectra and subsequent analysis follows precisely that described in Barklem et al. (2002). The most important aspects of the analysis are as follows. Synthetic profiles are computed assuming LTE line formation using one-dimensional LTE plane-parallel MARCS models (Asplund et al. 1997), with convection described by mixing-length theory with parameters $\alpha = 0.5$ and $\gamma = 0.5$. The most important line-broadening mechanisms for the wings are Stark broadening and self broadening, which are described by calculations of Stehlé & Hutcheon (1999) and Barklem et al. (2000), respectively. The fitting is done by minimization of the $\chi^2$ statistic, comparing the observed and synthetic profiles in spectral windows believed to be free of blends in the solar spectrum. To illustrate the fitting method and the temperature sensitivity of the hydrogen line profiles, Figure 4 shows fits to H$_\alpha$, H$_\beta$, and H$_\gamma$ line profiles for HE 2047–5612, a typical halo subgiant.

The choice to use LTE analysis follows the reasoning presented in Aoki et al. (2009) and bears repeating here. The assumption of LTE for the line wings has been shown to be questionable on the basis of theoretical non-LTE calculations (Barklem 2007), the role of hydrogen collisions being a major uncertainty. Those calculations suggest that the temperatures from LTE Balmer-line wings could be systematically too cool, by of order 100 K if hydrogen collisions are inefficient, although if collisions are efficient, LTE is not ruled out. Since there is no strong evidence favoring any particular hydrogen collision model, we calculate in LTE, as this temperature scale is well studied, and it is computationally most practical. However, we emphasize that LTE is not a safe middle ground, and will lead to temperatures that are systematically too cool, should departures from LTE exist in reality.

The individual Balmer lines have distinct characteristics and behaviors; so, as in Aoki et al. (2009), we chose not to give $T_{\text{eff}}$ from all lines equal weight in determining our final Balmer-line $T_{\text{eff}}$. H$_\alpha$ is often preferred over other lines in solar-type stars, for the reasons discussed by Fuhrmann et al. (1993). However, in metal-poor stars it is not clear that H$_\alpha$ is to be preferred. Blending of metal lines becomes unimportant, and H$_\beta$ becomes insensitive to gravity, while H$_\alpha$ is quite gravity sensitive (see Barklem et al. 2002, their Table 4) and rather insensitive to $T_{\text{eff}}$ (see Figure 6). These differences in behavior arise due to changes in the relative importance of Stark and self broadening. Moreover, the calculations by Barklem (2007) suggest that non-LTE effects, if they exist, will be largest in H$_\alpha$. H$_\beta$, while having similar sensitivities to H$_\beta$, is generally not as reliable as H$_\beta$. This is predominantly due to increased blending in this region of the spectrum, especially in CEMP stars with strong G bands, which affects both the local fitting of the line and nearby orders used to define the continuum placement. In addition, the $S/N$ of the spectra is generally much lower at H$_\gamma$ due to less flux in the blue. Considering all these factors, we judge H$_\beta$ as the most reliable line for determining $T_{\text{eff}}$, and so in combining the temperatures from H$_\alpha$, H$_\beta$, and H$_\gamma$, we have given H$_\beta$ double weight.

Thus, having determined $T_{\text{eff}}$ from each line for each spectrum ($T_{\text{eff}}$(H$_\alpha$), $T_{\text{eff}}$(H$_\beta$), $T_{\text{eff}}$(H$_\gamma$)), to determine the final hydrogen line profile $T_{\text{eff}}$(Balmer) for a star we employed the following procedure. For stars with multiple spectra, we first determined the mean $T_{\text{eff}}$(H$_\alpha$), $T_{\text{eff}}$(H$_\beta$), $T_{\text{eff}}$(H$_\gamma$) for the star, weighting each determination by the $S/N$ of the spectra. Next, we combined the mean $T_{\text{eff}}$(H$_\alpha$), mean $T_{\text{eff}}$(H$_\beta$), and mean $T_{\text{eff}}$(H$_\gamma$) temperatures using the 1:2:1 weighting into a final average $T_{\text{eff}}$(Balmer). Because the profiles are slightly depen-

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27 We chose not to analyze H$_\delta$ because of its lower $S/N$ on our spectra, which affects both local fitting and the ability to reliably apply the continuum normalisation techniques used here.
Fig. 6.— Fits to Hα, Hβ, and Hγ line profiles for HE 2047–5612, $T_{\text{eff}}$(Balmer) = 6040 K, assuming log $g$ = 3.6 and [Fe/H] = −3.2. The (black) full lines showing noise are the normalised observed spectra and the (red) smooth full lines the best fit synthetic profile (corresponding to $T_{\text{eff}}$=6040, 6020, 6080 K for each line, respectively). The (blue) dashed lines show the synthetic spectra calculated with models 200 K cooler and hotter than the best fit. The (yellow) shaded regions show the windows used for determining the $\chi^2$ statistic in the fitting, and residuals for these regions are shown in the bottom panel. The full vertical lines show the estimated limit of validity of the impact approximation in the self-broadening calculations, which is beyond the limit of the plot for Hγ. Note that the windows outside this region are rejected in the fitting, and thus no residual is plotted.

4.3. Medium Resolution Hδ Index HP2

A third, independent, temperature estimate was obtained from medium-resolution spectroscopy of the Hδ line index (HP2), calibrated as a function of $T_{\text{eff}}$ as described in the Appendix. We determined HP2 from the medium-resolution spectra of the candidate most metal-poor stars we observed with the 2.3m/DBS combination, and those we obtained from the SDSS Data Release 7, as described in Section 2. We now use the above calibration to estimate their effective temperatures, excluding two categories of objects. First, while our calibration may be applied with confidence for "normal" metal-poor stars, it would be inappropriate to use it for carbon-rich objects, because of CH absorption in the band-passes used to measure HP2. We thus do not present temperatures for the seven objects in our program sample that exhibit strong G bands: specifically, we exclude C-rich stars for which the Beers et al. (1999) G-band index $G'_{\text{Be}}$ is larger than $\sim 1.0$ Å (see Table 1). Secondly, we also exclude stars with fewer than 400 counts/1 Å pixel at 4100 Å, in an effort to exclude objects for which the poorer S/N might be expected to decrease the accuracy of the temperature estimate. The values of HP2 and the inferred values of $T_{\text{eff}}$ for the remaining 26 C-normal stars in our most metal-poor star sample are presented in columns (9) and (10) of Table 9.

4.4. Possible Systematic Differences in Temperature between Techniques

Figure 7 plots the differences between the temperature derived from fitting the overall flux and the temperatures derived from high-resolution hydrogen line profile fitting (LHS) and
the Hδ index (RHS). There are indications of some systematic differences in these figures. Compared to the temperatures derived from fitting the fluxes, the hydrogen line profiles yielded lower temperatures by $128 \pm 18$ K (36 stars), while the Hδ index yielded temperatures lower by $8 \pm 22$ K (25 stars).

As mentioned earlier, the temperatures derived from the hydrogen line profiles may be affected by the neglect of non-LTE and by remaining uncertainties in the broadening theory. The temperatures from flux fitting and hydrogen line fitting may both be affected by the use of 1D model atmospheres rather than 3D model atmospheres, but 3D effects are more likely for the hydrogen lines than the stellar energy distributions [Asplund 2005]. We also note that the temperatures from flux fitting are in agreement with those from the infrared flux method for those metal-poor stars in common. Future work by P.S.B. and M.A. is proposed to ascertain the reason or reasons for the cooler hydrogen line temperatures. There is an insignificant difference between the mean flux temperature and the empirically-calibrated mean Hδ index temperature.

In the absence of compelling reasons for discounting any of the temperature derivation techniques, we have taken a mean of the derived temperatures to use for our high resolution abundance analysis (Paper II), but note that these mean temperatures may be about 50 K cooler than the infrared flux method temperature scale. Our final $T_{\text{eff}}$ and their standard error of the mean are presented in columns (11) and (12) of Table 9.

While spectrophotometry, in principle, remains the best way of obtaining stellar parameters, modern wide-field broadband multicolor surveys such as SDSS, and in particular SkyMapper [Keller et al. 2007], will provide precise photometric indices that can be calibrated using synthetic photometry from model atmosphere fluxes to provide accurate temperatures, and good estimates of gravity and metallicity. Interstellar reddening, however, remains an issue for all photometric techniques, emphasizing the continuing necessity of hydrogen line fitting and the importance of further theoretical work on the formation of hydrogen lines in cool stars.

5. SUMMARY

We report the discovery of 34 stars in the Hamburg/ESO Survey for metal-poor stars and the Sloan Digital Sky Survey that have $[\text{Fe/H}] \lesssim -3.0$. Ten of them are newly discovered objects having $[\text{Fe/H}] < -3.5$. We have obtained high-resolution, high-$S/N$ spectra of them and four other extremely metal-poor stars (three of which have $[\text{Fe/H}] < -3.5$), and present equivalent widths and radial velocities for this sample.

$T_{\text{eff}}$ has been determined for these objects, employing three independent techniques. First, we analyzed medium-resolution spectra to obtain absolute fluxes. These were fit using model atmosphere fluxes to provide spectrophotometric $T_{\text{eff}}$ and $\log g$, with approximate $[\text{M/H}]$ and reddening. Second, we fit the wings of the Hα, Hβ, and Hγ lines, measured from our echelle spectra, to model atmosphere line profiles. Although there are some caveats concerning our understanding of the formation of these lines, this technique provides a reliable and reddening-independent method of temperature determination. Finally, we used the observed Hδ index, HP2, together with a calibration of HP2 as a function of $T_{\text{eff}}$, for a set of stars that have well-established temperatures, to obtain a third $T_{\text{eff}}$ estimate.

There are possible systematic differences in the temperatures derived using these three techniques, of order 100 K, and future work is needed to clarify the origin of these differences. Nevertheless, for our purposes, we adopted the average of the three determinations. The mean (internal) error of the resulting temperatures is 63 K, with a dispersion of 33 K.

The data presented here have been analyzed in Papers II, III, and IV of this series (Yong et al. 2012a, b, and Norris et al. 2012a, respectively), which includes a homogeneous re-analysis of similar data available in the literature. This has yielded relative chemical abundances for a total of ~86 stars having $[\text{Fe/H}] \lesssim -3.0$ (and some 32 with $[\text{Fe/H}] \lesssim -3.5$), which have been used to further constrain the conditions that existed at the earliest times.

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on Siding Spring Mountain, as described in Section 2.1 for our observations of candidate most metal-poor stars. The sample been taken from the work of Casagrande et al. (2010), who used the infrared flux method. Second, 14 metal-poor red giants broadband Hδ red giants with two determinations of index, HP2, of Beers et al. (1999, their Section 3.1.1). The data for our calibration stars are presented in Table 10, where the absolute mean difference was 5 K with dispersion 56 K. The calibration data are...
### Table 10

Hδ indices and $T_{\text{eff}}$ for calibration stars

| Star       | HP2 (Å) | $T_{\text{eff}}$ (K) | Source$^a$ |
|------------|---------|----------------------|------------|
| BD +3 740  | 4.79    | 6419                 | 1          |
| BD +9 2190 | 4.92    | 6477                 | 1          |
| BD +26 3578| 4.54    | 6425                 | 1          |
| BD –13 3442| 4.58    | 6434                 | 1          |
| CD –24 17504| 4.12   | 6455                 | 1          |
| CD –33 1173| 5.02    | 6548                 | 1          |
| CD –38 245 | 1.12    | 4800                 | 2          |
| BS 16477-003| 1.32   | 4900                 | 2          |
| CS 22169-035| 0.74    | 4662                 | 2.3        |
| CS 22172-002| 1.06    | 4838                 | 2.3        |
| CS 22186-025| 1.20    | 4900                 | 2          |
| CS 22189-009| 0.99    | 4887                 | 2.3        |
| CS 22873-166| 0.69    | 4550                 | 2          |
| CS 22891-209| 1.09    | 4725                 | 2.3        |
| CS 22952-015| 1.04    | 4900                 | 2          |
| CS 22953-003| 1.37    | 5100                 | 2          |
| CS 29491-053| 0.84    | 4700                 | 2          |
| G 4-37   | 4.19    | 6340                 | 1          |
| G 64-12  | 4.69    | 6464                 | 1          |
| G 64-37  | 4.71    | 6584                 | 1          |
| G 186-26 | 4.30    | 6375                 | 3          |
| HD 140283| 2.69    | 5777                 | 1          |
| LP 651-4 | 4.58    | 6500                 | 3          |
| LP 815-43| 4.92    | 6535                 | 1          |

$^a$ $T_{\text{eff}}$ sources: 1 = Casagrande et al. (2010); 2 = Cayrel et al. (2004); and 3 = Present work.

![Graph](image-url) - $T_{\text{eff}}$ versus HP2 for calibrating stars. Filled black circles represent dwarfs (and one subgiant) from Casagrande et al. (2010); open black circles are dwarfs from the present work; filled red boxes are giants from Cayrel et al. (2004); and open red boxes are the average values for giants from Cayrel et al. (2004) and the present work. The red line is the fitted quadratic relation.
