SPECTROSCOPIC STUDIES OF EXTREMELY METAL-POOR STARS WITH THE SUBARU HIGH-DISPERSION SPECTROGRAPH. IV. THE $\alpha$-ELEMENT–ENHANCED METAL-POOR STAR BS 16934–002

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ABSTRACT
A detailed elemental abundance analysis has been carried out for the very metal-poor ([Fe/H] = −2.7) star BS 16934–002, which was identified in our previous work as a star exhibiting large overabundances of Mg and Sc. A comparison of the abundance pattern of this star with that of the well-studied metal-poor star HD 122563 indicates excesses of O, Na, Mg, Al, and Sc in BS 16934–002. Of particular interest, no excess of C or N is found in this object, in contrast to CS 22949–037 and CS 29498–043, two previously known carbon-rich, extremely metal-poor stars with excesses of the $\alpha$-elements. No established nucleosynthesis model exists that explains the observed abundance pattern of BS 16934–002. A supernova model, including mixing and fallback and assuming severe mass loss before explosion, is discussed as a candidate progenitor of BS 16934–002.

Subject headings: nuclear reactions, nucleosynthesis, abundances — stars: abundances — stars: individual (BS 16934–002) — stars: Population II — supernovae: general

Online material: color figures

1. INTRODUCTION
Observational studies of stellar chemical compositions over the past few decades have revealed the presence of moderate overabundances in $\alpha$-elements (e.g., O, Mg, and Ca) in the majority of metal-deficient stars in the halo of the Galaxy (e.g., McWilliam 1997, and references therein). This observation is usually interpreted as arising from the expected dominant contribution of the yields of core-collapse supernovae in the early Galaxy, as compared to the yields of Type Ia supernovae, which provide a significant amount of iron, but at later times.

Recently, however, a handful of metal-poor stars have been identified with $[\alpha/Fe]$ abundance ratios that are quite different from this trend. A few stars are known to exhibit quite low $[\alpha/Fe]$ ratios (e.g., Ivans et al. 2003), while another small set of stars is known to exhibit significantly high ratios (e.g., $[\text{Mg}/\text{Fe}] \sim +1.8$; see McWilliam et al. 1995; Norris et al. 2001; Depagne et al. 2002; Aoki et al. 2002, 2004). Although the number of these anomalous stars remains small, their presence indicates that their nucleosynthesis histories apparently differ from the great majority of halo stars.

Our previous study (Aoki et al. 2005) identified a new $\alpha$-enhanced, very metal-poor star, BS 16934–002, with $[\text{Mg}/\text{Fe}] = +1.25$. A clear difference between this star and the previously known $\alpha$-rich, metal-poor stars (CS 22949–037 and CS 29498–043) is that no excess of C is found in BS 16934–002; we suggest that such a star be referred to as an alpha-enhanced metal-poor (AEMP) star. In order to investigate the astrophysical origin of the $\alpha$-enhancement in this so far unique object, we obtained a higher quality spectrum of BS 16934–002 and performed a more detailed elemental abundance analysis. One important result of this study is the measurement of O and Na abundances for BS 16934–002, which are also clearly higher than the typical values found in other very metal-poor halo stars. To avoid uncertainties arising from systematic errors in the abundance analyses and evolutionary effects on the surface chemical composition, the abundance ratios of each element are obtained with respect to the well-studied metal-deficient star HD 122563, which has atmospheric parameters similar to those of BS 16934–002. Details of our observations and abundance analyses are reported in § 2 and § 3, respectively. We discuss the implications of the observed excesses of the $\alpha$-elements in this star and offer possible interpretations in § 4.

2. OBSERVATIONS
High-resolution spectroscopy was obtained for BS 16934–002 with the High Dispersion Spectrograph (HDS; Noguchi et al. 2002) of the Subaru Telescope (Table 1). A blue spectrum

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10 [A/B] = $\log (N_A/N_H) - \log (N_B/N_H)$, and $\epsilon_A = \log (N_A/N_B) + 12$ for elements A and B.

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was obtained in our previous study (Aoki et al. 2005). The new spectrum covers the wavelength range from 4030 to 6800 Å, with an absence of data from 5350 to 5450 Å due to the physical gap between the two CCDs. The resolving power is $R = 60,000$, which is slightly higher than that of the previous observation for the blue range (Aoki et al. 2005). For comparison purposes, the bright metal-poor giant HD 122563, which has atmospheric parameters quite similar to those of BS 16934−002, was also observed with the same spectrograph setup. Rapidly rotating, early-type stars were observed in each run to divide out telluric absorption features.

Standard data reduction procedures (bias subtraction, flatfielding, background subtraction, extraction, and wavelength calibration) are carried out with the IRAF echelle package12 as described by Aoki et al. (2005). Telluric absorption features are corrected using the spectra of standard stars (see §3.1). The signal-to-noise (S/N) ratios achieved are provided in Table 1, as estimated from the peak counts of the spectra at ∼4500 Å.

Equivalent widths for prominent absorption lines are measured by fitting Gaussian profiles. Since the spectral resolution is slightly different between the present work and that of Aoki et al. (2005), we did not combine the spectra from these two studies. Instead, we adopt the means of the equivalent widths for the lines in common, as measured from the individual spectra. Figure 1 shows comparisons of the equivalent widths measured from these two studies. Since the agreement is quite good, we apply no corrections to the measured values. The equivalent widths finally adopted for the abundance analysis are listed in Table 2. The root mean square (rms) of the difference of the two measurements is 4 mA.

Radial velocities are measured using clean Fe i lines; the results are provided in Table 1. No significant change of heliocentric radial velocity was found for BS 16934−002 between the four observations from 2001 April to 2004 May (see Aoki et al. 2005). Hence, there exists no evidence of binarity for BS 16934−002 or for HD 122563, based on the data obtained thus far.

The equivalent widths of the interstellar Na i D1 and D2 lines for BS 16934−002 are 114.4 and 159.6 mA, respectively. The empirical relations between the strength of the interstellar absorption of Na i D2 and interstellar reddening by Munari & Zwitter (1997) provide an estimate of $E(B - V) = 0.050$. This value supports the independent estimate for reddening obtained from the dust maps of Schlegel et al. [1998; $E(B - V) = 0.032$], which was adopted by Aoki et al. (2005) in the determination of the effective temperature for this star.

### 3. ABUNDANCE ANALYSES AND RESULTS

As in our previous work, a standard analysis using the model atmospheres of Kurucz (1993) is performed for the measured

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**TABLE 1**

| Star          | Wavelength (Å) | Exposurea (minutes) | S/Nb | Observation Date (JD) | Radial Velocity (km s⁻¹) |
|---------------|----------------|---------------------|------|-----------------------|--------------------------|
| BS 16934−002  | 4030–6800      | 60 (2)              | 100/1| 2004 May 31 (2,453,158) | 82.5 ± 0.3               |
| HD 122563     | 4030–6800      | 2 (2)               | 300/1| 2005 Jun 19 (2,453,541) | −26.0 ± 0.2              |

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12 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
| Species      | Wavelength | log g | L.E.P. | HD 122563 | BS 16934–002 |
|--------------|------------|-------|--------|-----------|--------------|
| O I          | 6300.300   | -9.820| 0.000  | 7.2       | 14.3         |
| O I          | 6363.776   | -10.303| 0.020  | 2.2       | 5.0          |
| Na I         | 5682.633   | -0.700 | 2.102  | 1.3       | 8.7          |
| Na I         | 5688.204   | -0.412 | 2.104  | 2.8       | 17.7         |
| Na I         | 5889.951   | 0.101  | 0.000  | ...       | 225.6        |
| Na I         | 5895.924   | -0.197 | 0.000  | ...       | 212.0        |
| Mg I         | 3829.355   | -0.210 | 2.709  | 182.1     | ...          |
| Mg I         | 3986.753   | -1.030 | 4.346  | ...       | 35.4         |
| Mg I         | 4057.505   | -0.890 | 4.346  | ...       | 72.8         |
| Mg I         | 4167.271   | -0.770 | 4.346  | 54.4      | 84.6         |
| Mg I         | 4571.096   | -5.688 | 0.000  | 84.8      | 113.3        |
| Mg I         | 4702.991   | -0.520 | 4.346  | 73.8      | 106.8        |
| Mg I         | 5172.685   | -0.380 | 2.712  | 201.7     | ...          |
| Mg I         | 5183.604   | -0.160 | 2.717  | 221.8     | ...          |
| Mg I         | 5528.404   | -0.490 | 4.346  | 77.6      | 112.9        |
| Mg I         | 5711.088   | -1.720 | 4.346  | 11.7      | 31.7         |
| Al I         | 3944.006   | -0.644 | 0.000  | 163.0     | ...          |
| Al I         | 3961.520   | -0.340 | 0.014  | 139.0     | 153.3        |
| Si I         | 3905.523   | -0.980 | 1.909  | 196.6     | ...          |
| Si I         | 4102.936   | -2.910 | 1.909  | 88.8      | 78.5         |
| Ca I         | 4226.728   | 0.244  | 0.000  | ...       | 201.5        |
| Ca I         | 4283.010   | -0.220 | 1.886  | 62.7      | 68.3         |
| Ca I         | 4318.652   | -0.210 | 1.899  | 53.7      | 52.7         |
| Ca I         | 4425.441   | -0.360 | 1.879  | 49.1      | 45.9         |
| Ca I         | 4435.688   | -0.520 | 1.886  | 41.5      | 38.2         |
| Ca I         | 4454.781   | 0.260  | 1.899  | ...       | 83.3         |
| Ca I         | 4455.887   | -0.530 | 1.899  | 39.8      | 43.9         |
| Ca I         | 5262.244   | -0.471 | 2.521  | 34.2      | 44.6         |
| Ca I         | 5581.971   | -0.555 | 2.523  | 13.1      | 12.0         |
| Ca I         | 5588.757   | 0.358  | 2.526  | 49.6      | 49.4         |
| Ca I         | 5590.120   | -0.571 | 2.521  | 12.3      | 12.0         |
| Ca I         | 5594.468   | 0.097  | 2.523  | 36.7      | 36.2         |
| Ca I         | 5598.487   | -0.087 | 2.521  | 29.9      | 28.6         |
| Ca I         | 5601.285   | -0.523 | 2.526  | 13.1      | 10.7         |
| Ca I         | 5857.452   | 0.240  | 2.933  | 24.3      | 25.5         |
| Ca I         | 6102.722   | -0.770 | 1.879  | 36.8      | 39.4         |
| Ca I         | 6122.219   | -0.320 | 1.886  | 68.5      | 64.4         |
| Ca I         | 6169.055   | -0.797 | 2.523  | 9.4       | 10.3         |
| Ca I         | 6169.559   | -0.478 | 2.526  | 16.3      | 14.5         |
| Ca I         | 6439.073   | 0.390  | 2.526  | 58.8      | 61.4         |
| Ca I         | 6449.810   | -0.502 | 2.521  | 16.5      | 16.0         |
| Ca I         | 6499.649   | -0.818 | 2.523  | 9.4       | 10.7         |
| Ca I         | 6717.685   | -0.524 | 2.709  | 11.1      | 13.0         |
| Sc I         | 4995.002   | -0.880 | 2.111  | 1.0       | ...          |
| Ti I         | 3904.784   | 0.030  | 0.900  | 29.6      | 35.3         |
| Ti I         | 3924.526   | -0.881 | 0.021  | 35.1      | 48.0         |
| Ti I         | 3989.759   | -0.142 | 0.021  | 71.7      | 86.5         |
| Ti I         | 3998.637   | 0.000  | 0.048  | 71.5      | 84.2         |
| Ti I         | 4008.928   | -1.016 | 0.021  | 29.5      | 41.4         |
| Ti I         | 4512.733   | -0.424 | 0.836  | 14.1      | 27.4         |
| Ti I         | 4533.239   | 0.532  | 0.848  | 52.9      | 67.4         |
| Ti I         | 4534.775   | 0.336  | 0.836  | 42.2      | 57.2         |
| Ti I         | 4535.567   | 0.120  | 0.826  | 36.2      | 50.1         |
| Ti I         | 4544.687   | -0.520 | 0.818  | 14.9      | 22.3         |
| Ti I         | 4548.763   | -0.298 | 0.826  | 17.9      | 28.0         |
| Ti I         | 4681.908   | -1.015 | 0.048  | 29.5      | 48.2         |
| Ti I         | 4981.730   | 0.560  | 0.848  | 62.2      | ...          |
| Ti I         | 4991.066   | 0.436  | 0.836  | 58.1      | 73.2         |
| Ti I         | 4999.501   | 0.306  | 0.826  | 50.2      | 66.6         |
| Ti I         | 5007.206   | 0.168  | 0.818  | 52.2      | 64.0         |
| Ti I         | 5009.645   | -2.023 | 0.021  | ...       | 5.7          |
| Ti I         | 5016.160   | -0.516 | 0.848  | 12.7      | 23.7         |
| Ti I         | 5020.024   | -0.358 | 0.836  | 18.3      | 30.1         |
| Ti I         | 5024.943   | -0.546 | 0.818  | 13.6      | 21.5         |
| Species | Wavelength | log g | L. E. P.\(^a\) |
|---------|------------|-------|---------------|
| Ti i    | 5035.902   | 0.260 | 1.460         |
| Ti i    | 5036.463   | 0.186 | 1.443         |
| Ti i    | 5038.396   | 0.069 | 1.430         |
| Ti i    | 5039.960   | -1.130| 0.020         |
| Ti i    | 5064.651   | -0.935| 0.048         |
| Ti i    | 5173.740   | -1.062| 0.000         |
| Ti i    | 5192.969   | -0.948| 0.021         |
| Ti i    | 5210.384   | -0.828| 0.048         |
| Ti i    | 6258.099   | -0.299| 1.443         |
| V i     | 4379.230   | 0.550 | 0.301         |
| V i     | 4786.499   | 0.110 | 2.074         |
| V i     | 5195.395   | -0.120| 2.278         |
| V i     | 6008.648   | -2.340| 1.183         |
| Cr i    | 3908.762   | -1.000| 1.004         |
| Cr i    | 4254.332   | -0.114| 0.000         |
| Cr i    | 4274.796   | -0.231| 0.000         |
| Cr i    | 4337.566   | -1.112| 0.968         |
| Cr i    | 4558.650   | -0.660| 4.070         |
| Cr i    | 4580.056   | -1.650| 0.941         |
| Cr i    | 4588.200   | -0.630| 4.070         |
| Cr i    | 4600.752   | -1.260| 1.004         |
| Cr i    | 4616.137   | -1.190| 0.983         |
| Cr i    | 4626.188   | -1.320| 0.968         |
| Cr i    | 4646.174   | -0.700| 1.030         |
| Cr i    | 4651.285   | -1.460| 0.983         |
| Cr i    | 4652.158   | -1.030| 1.004         |
| Cr i    | 5206.039   | 0.019 | 0.941         |
| Cr i    | 5247.564   | -1.640| 0.961         |
| Mn i    | 3823.508   | 0.058 | 2.143         |
| Mn i    | 4030.753   | -0.470| 0.000         |
| Mn i    | 4033.062   | -0.618| 0.000         |
| Mn i    | 4034.838   | -0.811| 0.000         |
| Mn i    | 4041.357   | 0.285 | 2.114         |
| Mn i    | 4754.048   | -0.086| 2.282         |
| Mn i    | 4783.432   | 0.042 | 2.298         |
| Mn i    | 4823.528   | 0.144 | 2.319         |
| Fe i    | 3787.880   | -0.859| 1.011         |
| Fe i    | 3805.342   | 0.310 | 3.301         |
| Fe i    | 3815.840   | 0.226 | 1.485         |
| Fe i    | 3827.823   | 0.062 | 1.557         |
| Fe i    | 3839.256   | -0.330| 3.047         |
| Fe i    | 3840.437   | -0.506| 0.990         |
| Fe i    | 3841.048   | -0.065| 1.608         |
| Fe i    | 3845.169   | -1.390| 2.424         |
| Fe i    | 3846.800   | -0.020| 3.251         |
| Fe i    | 3849.980   | -0.863| 1.010         |
| Fe i    | 3850.818   | -1.745| 0.990         |
| Fe i    | 3852.573   | -1.180| 2.176         |
| Fe i    | 3856.372   | -1.286| 0.052         |
| Fe i    | 3863.741   | -1.430| 2.692         |
| Fe i    | 3865.523   | -0.982| 1.011         |
| Fe i    | 3867.216   | -0.450| 3.017         |
| Fe i    | 3885.510   | -1.090| 2.424         |
| Fe i    | 3899.707   | -1.531| 0.087         |
| Fe i    | 3902.946   | -0.466| 1.557         |
| Fe i    | 3917.181   | -2.155| 0.990         |
| Fe i    | 3920.258   | -1.746| 0.121         |
| Fe i    | 3922.912   | -1.651| 0.052         |
| Fe i    | 3940.878   | -2.600| 0.958         |
| Fe i    | 3949.953   | -1.250| 2.176         |
| Fe i    | 3977.741   | -1.120| 2.198         |
| Fe i    | 4001.661   | -1.900| 2.176         |
| Fe i    | 4005.242   | -0.610| 1.557         |
| Fe i    | 4007.272   | -1.280| 2.759         |
| Fe i    | 4014.531   | -0.590| 3.047         |

\(^a\) L. E. P. = L. E. P. (eV)
| Species  | Wavelength | log $g$ | L. E. P. | HD 122563 | BS 16934—002 |
|----------|------------|--------|----------|-----------|--------------|
| Fe        | 4021.866  | -0.730 | 2.759    | 54.2      | ...          |
| Fe        | 4032.627  | -2.380 | 1.485    | 54.0      | 45.3         |
| Fe        | 4044.609  | -1.220 | 2.832    | 32.3      | ...          |
| Fe        | 4058.217  | -1.110 | 3.211    | 30.7      | 26.4         |
| Fe        | 4062.441  | -0.860 | 2.845    | 45.7      | 43.9         |
| Fe        | 4063.594  | 0.060  | 1.557    | 166.0     | 151.8        |
| Fe        | 4067.271  | -1.410 | 2.559    | 41.4      | 32.5         |
| Fe        | 4067.978  | -0.470 | 3.211    | 43.4      | 35.3         |
| Fe        | 4070.769  | -0.790 | 2.241    | 27.4      | 22.4         |
| Fe        | 4071.738  | -0.022 | 1.608    | 156.2     | 144.1        |
| Fe        | 4073.763  | -0.900 | 3.266    | 22.2      | ...          |
| Fe        | 4079.838  | -1.360 | 2.858    | 22.7      | 18.7         |
| Fe        | 4095.970  | -1.480 | 2.588    | ...       | 27.4         |
| Fe        | 4098.176  | -0.880 | 3.241    | 25.5      | ...          |
| Fe        | 4109.057  | -1.560 | 3.292    | 11.7      | 15.3         |
| Fe        | 4109.802  | -0.940 | 2.845    | 45.0      | 44.9         |
| Fe        | 4114.445  | -1.300 | 2.832    | 30.1      | 26.5         |
| Fe        | 4120.207  | -1.270 | 2.990    | 24.3      | 16.7         |
| Fe        | 4121.802  | -1.450 | 2.832    | 24.4      | 20.9         |
| Fe        | 4132.899  | -1.010 | 2.845    | 43.3      | 38.9         |
| Fe        | 4136.998  | -0.450 | 3.415    | 26.7      | 25.1         |
| Fe        | 4139.927  | -3.620 | 0.990    | ...       | 28.9         |
| Fe        | 4143.414  | -0.200 | 3.047    | 67.1      | 58.4         |
| Fe        | 4143.868  | -0.510 | 1.557    | 135.2     | 123.9        |
| Fe        | 4147.669  | -2.104 | 1.485    | 80.4      | 74.2         |
| Fe        | 4152.169  | -3.232 | 0.958    | 60.8      | 49.9         |
| Fe        | 4153.899  | -0.320 | 3.397    | 40.7      | 32.8         |
| Fe        | 4154.499  | -0.690 | 2.832    | 54.0      | 43.7         |
| Fe        | 4154.805  | -0.400 | 3.368    | 39.8      | 32.9         |
| Fe        | 4156.799  | -0.810 | 2.832    | 59.3      | 51.6         |
| Fe        | 4157.779  | -0.400 | 3.417    | 37.3      | 38.0         |
| Fe        | 4158.793  | -0.670 | 3.430    | 22.4      | 17.4         |
| Fe        | 4175.636  | -0.830 | 2.845    | 52.1      | 47.5         |
| Fe        | 4181.755  | -0.370 | 2.832    | 75.4      | 68.8         |
| Fe        | 4182.382  | -1.180 | 3.017    | 24.5      | 16.6         |
| Fe        | 4184.892  | -0.870 | 2.832    | 45.2      | 39.4         |
| Fe        | 4187.039  | -0.548 | 2.450    | 89.5      | 80.7         |
| Fe        | 4191.430  | -0.670 | 2.469    | 84.9      | ...          |
| Fe        | 4195.329  | -0.490 | 3.332    | 44.2      | 39.0         |
| Fe        | 4196.208  | -0.700 | 3.397    | 23.1      | 19.8         |
| Fe        | 4199.095  | 0.160  | 3.047    | 80.0      | 75.6         |
| Fe        | 4216.184  | -3.356 | 0.000    | 115.3     | 108.5        |
| Fe        | 4222.217  | -0.967 | 2.450    | ...       | 69.8         |
| Fe        | 4227.426  | 0.270  | 3.332    | 91.9      | ...          |
| Fe        | 4233.603  | -0.604 | 2.482    | 85.3      | 80.6         |
| Fe        | 4238.810  | -0.230 | 3.397    | 44.2      | 39.8         |
| Fe        | 4247.426  | -0.240 | 3.368    | 50.6      | 44.6         |
| Fe        | 4250.119  | -0.405 | 2.469    | 94.4      | 81.0         |
| Fe        | 4250.787  | -0.710 | 1.557    | 129.1     | ...          |
| Fe        | 4260.474  | 0.080  | 2.399    | 119.4     | 111.7        |
| Fe        | 4271.153  | -0.349 | 2.450    | 103.8     | 96.4         |
| Fe        | 4271.761  | -0.164 | 1.485    | 163.7     | 152.4        |
| Fe        | 4282.403  | -0.780 | 2.176    | 92.1      | 84.4         |
| Fe        | 4325.762  | 0.010  | 1.608    | 162.0     | 150.4        |
| Fe        | 4337.046  | -1.695 | 1.557    | 94.5      | ...          |
| Fe        | 4352.735  | -1.290 | 2.223    | 77.7      | 72.1         |
| Fe        | 4375.930  | -3.031 | 0.000    | 124.8     | 122.2        |
| Fe        | 4407.709  | -1.970 | 2.176    | 59.0      | ...          |
| Fe        | 4422.568  | -1.110 | 2.845    | 45.6      | ...          |
| Fe        | 4430.614  | -1.659 | 2.223    | 54.6      | 46.2         |
| Fe        | 4442.339  | -1.255 | 2.198    | 78.7      | 75.3         |
| Fe        | 4443.194  | -1.040 | 2.858    | 38.1      | 31.7         |
| Fe        | 4447.717  | -1.342 | 2.223    | 73.8      | 65.1         |
| Fe        | 4454.381  | -1.300 | 2.832    | ...       | 29.6         |
| Fe        | 4459.118  | -1.279 | 2.176    | 92.3      | 76.4         |
| Species | Wavelength | log gf  |
|---------|------------|--------|
| Fe      |            | L. E. P. (eV) | HD 122563 | BS 16934–002 |
| Fe      | 4461.653   | 3.210 0.087 | 119.0     | 112.4      |
| Fe      | 4466.552   | 0.600 2.832 | 86.3      | 77.0       |
| Fe      | 4476.019   | 0.820 2.845 | 67.6      | 57.3       |
| Fe      | 4484.220   | 0.860 3.603 | 17.2      | 16.6       |
| Fe      | 4489.739   | 3.966 0.121 | 87.4      | 80.6       |
| Fe      | 4490.083   | 1.580 3.017 | 9.6       | 6.6        |
| Fe      | 4494.563   | 1.136 2.198 | 84.6      | 77.9       |
| Fe      | 4528.614   | 0.822 2.176 | 102.8     | 96.4       |
| Fe      | 4531.148   | 2.155 1.485 | 84.9      | 74.8       |
| Fe      | 4592.651   | 2.449 1.557 | 68.3      | 63.0       |
| Fe      | 4602.941   | 2.210 1.485 | 82.5      | 78.1       |
| Fe      | 4611.185   | 2.720 2.851 | 15.3      | ...        |
| Fe      | 4632.912   | 2.913 1.608 | 34.4      | 28.0       |
| Fe      | 4647.435   | 1.350 2.949 | 24.3      | 21.1       |
| Fe      | 4678.846   | 0.830 3.603 | 17.9      | 16.4       |
| Fe      | 4691.411   | 1.520 2.990 | 20.1      | 20.5       |
| Fe      | 4707.274   | 1.080 3.241 | 28.5      | ...        |
| Fe      | 4710.283   | 1.610 3.018 | 15.6      | 14.8       |
| Fe      | 4733.591   | 2.990 1.485 | 40.3      | 35.3       |
| Fe      | 4736.772   | 0.750 3.211 | 44.1      | 36.0       |
| Fe      | 4786.807   | 1.610 3.017 | 15.6      | ...        |
| Fe      | 4789.650   | 0.960 3.547 | 12.1      | 8.7        |
| Fe      | 4859.741   | 0.760 2.876 | ...       | 53.2       |
| Fe      | 4871.318   | 0.360 2.865 | 79.4      | 73.2       |
| Fe      | 4872.138   | 0.570 2.882 | 68.1      | 59.7       |
| Fe      | 4890.755   | 0.390 2.876 | 80.2      | 70.6       |
| Fe      | 4891.492   | 0.110 2.851 | 93.5      | 84.7       |
| Fe      | 4903.310   | 0.930 2.882 | 50.7      | 45.3       |
| Fe      | 4918.994   | 0.340 2.865 | 81.4      | 75.8       |
| Fe      | 4920.502   | 0.070 2.833 | 104.1     | 96.6       |
| Fe      | 4924.770   | 2.256 2.279 | 30.3      | 22.6       |
| Fe      | 4938.814   | 1.080 2.876 | 42.3      | 35.0       |
| Fe      | 4939.687   | 3.340 0.859 | 71.1      | 61.9       |
| Fe      | 4946.388   | 1.170 3.368 | 15.9      | ...        |
| Fe      | 4966.088   | 0.870 3.332 | 31.3      | 26.6       |
| Fe      | 4973.102   | 0.950 3.960 | 8.8       | ...        |
| Fe      | 4994.130   | 2.956 0.915 | 82.2      | 74.5       |
| Fe      | 5001.870   | 0.050 3.880 | 31.6      | 25.0       |
| Fe      | 5006.119   | 0.610 2.833 | 71.6      | 66.2       |
| Fe      | 5012.068   | 2.642 0.859 | 110.5     | 105.3      |
| Fe      | 5014.942   | 0.300 3.943 | 23.3      | 18.0       |
| Fe      | 5022.336   | 0.530 3.984 | 13.8      | 12.6       |
| Fe      | 5027.225   | 1.890 3.640 | 9.9       | ...        |
| Fe      | 5028.127   | 1.120 3.573 | 9.5       | 4.2        |
| Fe      | 5041.072   | 3.090 0.958 | 86.1      | 81.0       |
| Fe      | 5041.756   | 2.200 1.485 | 94.3      | 87.3       |
| Fe      | 5044.210   | 2.040 2.850 | 9.6       | ...        |
| Fe      | 5049.820   | 1.344 2.279 | 74.4      | 66.5       |
| Fe      | 5051.635   | 2.795 0.915 | 100.5     | 92.5       |
| Fe      | 5060.080   | 5.460 0.000 | 19.4      | 16.2       |
| Fe      | 5068.766   | 1.040 2.940 | 39.7      | 31.8       |
| Fe      | 5074.749   | 0.200 4.220 | 17.5      | 14.7       |
| Fe      | 5079.224   | 2.067 2.198 | 43.3      | 36.9       |
| Fe      | 5079.740   | 3.220 0.990 | 70.0      | ...        |
| Fe      | 5080.950   | 3.090 3.267 | 17.1      | ...        |
| Fe      | 5083.339   | 2.958 0.958 | 86.6      | 79.3       |
| Fe      | 5090.770   | 0.360 4.260 | 7.1       | 4.8        |
| Fe      | 5098.697   | 2.030 2.176 | 54.7      | 47.8       |
| Fe      | 5123.720   | 3.068 1.011 | 76.8      | ...        |
| Fe      | 5125.117   | 0.140 4.220 | 17.5      | 14.0       |
| Fe      | 5127.359   | 3.307 0.915 | 70.4      | 65.8       |
| Fe      | 5131.146   | 2.510 2.223 | 20.6      | 16.2       |
| Fe      | 5133.689   | 0.140 4.178 | 31.0      | 26.8       |
| Fe      | 5137.382   | 0.400 4.178 | 14.4      | 11.5       |
| Fe      | 5141.739   | 1.964 2.424 | 19.3      | 18.1       |

| Species | Wavelength | log g | L. E. P. | HD 122563 | BS 16934—002 |
|---------|------------|-------|----------|------------|---------------|
| Fe      | 5142.929   | −3.080 | 0.958   | 82.5       | 73.1          |
| Fe      | 5150.839   | −3.003 | 0.990   | 73.4       | 61.6          |
| Fe      | 5151.911   | −3.322 | 1.011   | 61.7       | 54.0          |
| Fe      | 5162.273   | 0.020  | 4.178   | 26.2       | 19.5          |
| Fe      | 5166.282   | −4.195 | 0.000   | 92.2       | 85.4          |
| Fe      | 5171.597   | −1.793 | 1.485   | 108.3      | 104.3         |
| Fe      | 5191.455   | −0.550 | 3.038   | 60.4       | 51.0          |
| Fe      | 5192.344   | −0.420 | 2.998   | 69.8       | 61.4          |
| Fe      | 5194.942   | −2.090 | 1.557   | 89.9       | 85.2          |
| Fe      | 5198.717   | −2.135 | 2.223   | 37.1       | 31.4          |
| Fe      | 5202.336   | −1.838 | 2.176   | 59.2       | 48.8          |
| Fe      | 5204.583   | −4.332 | 0.087   | 128.3      | ...           |
| Fe      | 5216.274   | −2.150 | 1.608   | 82.8       | 78.5          |
| Fe      | 5217.390   | −1.070 | 3.211   | 22.7       | 19.7          |
| Fe      | 5255.525   | −4.789 | 0.110   | 44.8       | 39.1          |
| Fe      | 5232.940   | −0.600 | 2.940   | 92.2       | 85.3          |
| Fe      | 5242.491   | −0.970 | 3.634   | 11.7       | 9.9           |
| Fe      | 5247.050   | −4.946 | 0.087   | 36.7       | 33.2          |
| Fe      | 5250.210   | −4.938 | 0.121   | 35.4       | 28.5          |
| Fe      | 5250.646   | −2.180 | 2.196   | 40.2       | 33.2          |
| Fe      | 5254.956   | −4.764 | 0.110   | ...        | 42.2          |
| Fe      | 5263.305   | −0.879 | 3.266   | 27.8       | 19.9          |
| Fe      | 5269.537   | −1.321 | 0.859   | 165.8      | 156.2         |
| Fe      | 5281.790   | −0.830 | 3.038   | 44.8       | 42.3          |
| Fe      | 5283.621   | −0.432 | 3.241   | 52.1       | 45.9          |
| Fe      | 5302.300   | −0.720 | 3.283   | ...        | 28.2          |
| Fe      | 5307.361   | −2.987 | 1.608   | 33.7       | 28.8          |
| Fe      | 5324.179   | −0.103 | 3.211   | 72.4       | 65.0          |
| Fe      | 5328.039   | −1.466 | 0.915   | 159.7      | 149.9         |
| Fe      | 5328.531   | −1.850 | 1.557   | 107.1      | 96.6          |
| Fe      | 5332.900   | −2.780 | 1.557   | 44.6       | 38.5          |
| Fe      | 5501.465   | −3.050 | 0.958   | 87.7       | 79.9          |
| Fe      | 5506.778   | −2.797 | 0.990   | 99.8       | 91.4          |
| Fe      | 5569.618   | −0.540 | 3.417   | 37.5       | 31.1          |
| Fe      | 5572.842   | −0.275 | 3.397   | 50.8       | 44.6          |
| Fe      | 5576.088   | −1.000 | 3.430   | 22.4       | 18.3          |
| Fe      | 5586.755   | −0.096 | 3.368   | 61.3       | 57.8          |
| Fe      | 5615.644   | 0.050  | 3.332   | 72.2       | 67.6          |
| Fe      | 5624.542   | −0.755 | 3.417   | 26.9       | 22.5          |
| Fe      | 5658.816   | −0.793 | 3.397   | 26.8       | 22.6          |
| Fe      | 5686.529   | −0.450 | 4.549   | 3.0        | ...           |
| Fe      | 5701.543   | −2.216 | 2.559   | 14.8       | 12.2          |
| Fe      | 6065.481   | −1.530 | 2.609   | 43.3       | 39.4          |
| Fe      | 6136.614   | −1.400 | 2.453   | 66.1       | 58.3          |
| Fe      | 6137.691   | −1.403 | 2.588   | 56.5       | 48.4          |
| Fe      | 6191.558   | −1.420 | 2.433   | 64.0       | 56.9          |
| Fe      | 6200.312   | −2.437 | 2.609   | 9.4        | 8.1           |
| Fe      | 6213.429   | −2.480 | 2.223   | 20.7       | 16.7          |
| Fe      | 6219.280   | −2.433 | 2.198   | 26.8       | 23.6          |
| Fe      | 6230.723   | −1.281 | 2.559   | 67.9       | 60.8          |
| Fe      | 6246.318   | −0.733 | 3.603   | ...        | 16.0          |
| Fe      | 6252.555   | −1.687 | 2.404   | 53.8       | 48.6          |
| Fe      | 6254.257   | −2.443 | 2.279   | 24.4       | 21.7          |
| Fe      | 6265.134   | −2.550 | 2.176   | 24.9       | 20.1          |
| Fe      | 6301.499   | −0.718 | 3.654   | 17.5       | 14.2          |
| Fe      | 6322.685   | −2.426 | 2.588   | 11.2       | 7.8           |
| Fe      | 6355.330   | −2.180 | 2.198   | 37.7       | 34.9          |
| Fe      | 6336.835   | −1.050 | 3.686   | 12.9       | 10.5          |
| Fe      | 6393.601   | −1.432 | 2.433   | 61.0       | 53.2          |
| Fe      | 6400.000   | −0.290 | 3.603   | 39.5       | 33.6          |
| Fe      | 6411.649   | −0.595 | 3.654   | 23.1       | 20.0          |
| Fe      | 6421.350   | −2.027 | 2.279   | 46.3       | 39.6          |
| Fe      | 6430.845   | −2.006 | 2.176   | 55.6       | 50.2          |
| Fe      | 6498.940   | −0.099 | 0.958   | 9.7        | ...           |
| Fe      | 6592.913   | −1.470 | 2.728   | ...        | 33.2          |
| Species  | Wavelength (Å) | log f | L. E. P. (eV) HD 122563 | BS 16934—002 |
|---------|----------------|-------|-------------------------|--------------|
| Fe i    | 6593.868       | −2.422| 2.433                   | 15.9         |
| Fe i    | 6663.440       | −2.479| 2.424                   | 15.9         |
| Fe i    | 6677.986       | −1.420| 2.692                   | 50.7         |
| Fe i    | 6750.151       | −2.621| 2.424                   | 12.2         |
| Co i    | 3842.047       | −0.770| 0.923                   | 56.7         |
| Co i    | 3845.468       | 0.010 | 0.923                   | 93.6         |
| Co i    | 3873.120       | −0.660| 0.432                   | 129.9        |
| Co i    | 3881.869       | −1.130| 0.582                   | 78.0         |
| Co i    | 3995.306       | −0.220| 0.923                   | 82.7         |
| Co i    | 4020.998       | −2.070| 0.432                   | 40.6         |
| Co i    | 4110.532       | −1.080| 1.049                   | 39.0         |
| Ni i    | 4121.318       | −0.320| 0.923                   | 91.4         |
| Ni i    | 3807.144       | −1.220| 0.423                   | 115.4        |
| Ni i    | 3858.301       | −0.951| 0.423                   | 126.6        |
| Ni i    | 4648.659       | −0.160| 3.420                   | 16.2         |
| Ni i    | 4714.421       | 0.230 | 3.380                   | 31.6         |
| Ni i    | 4855.414       | 0.000 | 3.542                   | ...          |
| Ni i    | 4980.161       | −0.110| 3.606                   | 15.6         |
| Ni i    | 5017.591       | −0.080| 3.539                   | 14.5         |
| Ni i    | 5035.374       | 0.290 | 3.635                   | 21.7         |
| Ni i    | 5080.523       | 0.130 | 3.655                   | 21.8         |
| Ni i    | 5084.081       | 0.030 | 3.678                   | 12.4         |
| Ni i    | 5137.075       | −1.990| 1.676                   | 35.5         |
| Ni i    | 5578.734       | −2.640| 1.676                   | 6.4          |
| Ni i    | 5754.675       | −2.330| 1.935                   | 11.8         |
| Ni i    | 6108.121       | −2.450| 1.676                   | 10.9         |
| Ni i    | 6643.641       | −2.300| 1.676                   | 25.1         |
| Ni i    | 6767.778       | −2.170| 1.826                   | 23.4         |
| Zn i    | 4722.150       | −0.390| 4.030                   | 14.2         |
| Zn ii   | 4810.530       | −0.170| 4.080                   | 18.8         |
| Se i    | 4246.820       | 0.240 | 0.315                   | 133.0        |
| Se ii   | 4324.998       | −0.440| 0.595                   | 96.7         |
| Se ii   | 4415.544       | −0.670| 0.595                   | 74.2         |
| Se ii   | 5031.010       | −0.400| 1.357                   | 41.9         |
| Se ii   | 5239.811       | −0.770| 1.455                   | 20.3         |
| Se ii   | 5318.374       | −2.010| 1.357                   | 2.9          |
| Se ii   | 5526.785       | 0.020 | 1.768                   | 41.4         |
| Se ii   | 5641.000       | −1.130| 1.500                   | 13.3         |
| Se ii   | 5657.907       | −0.600| 1.507                   | 32.1         |
| Se ii   | 5658.362       | −1.210| 1.497                   | 10.6         |
| Se ii   | 5667.164       | −1.310| 1.500                   | 8.3          |
| Se ii   | 5669.055       | −1.200| 1.500                   | 10.1         |
| Se ii   | 5684.214       | −1.070| 1.507                   | 11.8         |
| Se ii   | 6604.578       | −1.310| 1.357                   | 8.7          |
| Ti ii   | 3813.394       | −2.020| 0.607                   | 97.0         |
| Ti ii   | 3882.291       | −1.710| 1.116                   | ...          |
| Ti ii   | 4012.396       | −1.750| 0.574                   | 104.8        |
| Ti ii   | 4025.120       | −1.980| 0.607                   | 86.1         |
| Ti ii   | 4028.355       | −1.000| 1.892                   | 55.4         |
| Ti ii   | 4053.829       | −1.210| 1.893                   | 42.6         |
| Ti ii   | 4161.527       | −2.160| 1.064                   | 53.3         |
| Ti ii   | 4163.634       | −0.400| 2.590                   | 45.0         |
| Ti ii   | 4184.309       | −2.510| 1.080                   | 30.7         |
| Ti ii   | 4330.723       | −2.060| 1.180                   | 46.9         |
| Ti ii   | 4337.876       | −1.130| 1.080                   | 101.4        |
| Ti ii   | 4395.833       | −1.970| 1.243                   | 49.4         |
| Ti ii   | 4399.786       | −1.270| 1.237                   | 97.1         |
| Ti ii   | 4417.715       | −1.430| 1.165                   | 99.6         |
| Ti ii   | 4418.306       | −1.990| 1.237                   | 53.2         |
| Ti ii   | 4441.731       | −2.410| 1.180                   | 39.7         |
| Ti ii   | 4443.775       | −0.700| 1.080                   | 119.9        |
| Ti ii   | 4444.536       | −2.210| 1.116                   | 48.1         |
| Ti ii   | 4450.503       | −1.510| 1.084                   | 88.5         |
| Ti ii   | 4464.461       | −2.080| 1.161                   | 68.0         |
| Ti ii   | 4468.517       | −0.600| 1.131                   | 121.7        |

**TABLE 2—Continued**
equivalent widths for most elements, while a spectrum synthesis technique is applied to the molecular bands of CH and CN and some additional weak atomic lines. We adopt the atmospheric parameters determined by Aoki et al. (2005); these are listed in Table 3. An exception is the microturbulent velocity \( \xi_{\text{micro}} \), which is redetermined from the Fe i lines by demanding no dependence of the derived abundance on equivalent widths. The \( \xi_{\text{micro}} \) values agree well with the result of the previous analysis (the difference is 0.1 km s\(^{-1}\)). The abundance results are presented in Table 4.

### 3.1. Carbon, Nitrogen, and Oxygen

The carbon abundance is redetermined from the CH 4322 Å band, as in our previous analysis, for the new spectrum of BS...
16934−002 (Fig. 2). The agreement with the previous result is fairly good. The nitrogen abundance is determined from the CN 3883 Å band in the blue spectrum of Aoki et al. (2005), which was not analyzed in our previous work (Fig. 3). The absorption features of CH and CN are quite similar for BS 16934−002 and HD 122563. The [C/Fe] in both objects is underabundant with respect to the solar ratio ([C/Fe] ≈ −0.3), while [N/Fe] is moderately overabundant ([N/Fe] ≈ +0.6; see § 4).

The oxygen abundances are determined from the [O i] 6300 and 6363 Å lines through a standard analysis. The stellar absorption lines of the [O i] in BS 16934−002 are well separated from sky emission lines due to its large Doppler shift. The telluric absorption features appearing in the original spectra are indicated. A comparison of the [O i] absorption in these two stars clearly shows the excess of oxygen in BS 16934−002 with respect to HD 122563. We note that the abundance analyses for carbon and nitrogen are made including the oxygen overabundance. The effect of the oxygen excess on the derived carbon and nitrogen abundance is about 0.1 dex or smaller.

The oxygen abundance of HD 122563 was studied by Barbuy et al. (2003), who used three abundance indicators (the [O i] 6300 Å line, the near-infrared O i triplet, and the OH molecular lines at 1.5−1.7 μm). Our result ([O/Fe] = +0.7) agrees well with the value ([O/Fe] = +0.6) they obtained from the [O i] 6300 Å line. Although there exists some discrepancy in oxygen abundances determined from the different indicators, the excess of BS 16934−002 estimated from the [O i] feature, compared with that of HD 122563, is robust.

### Table 3

| Star       | $T_{\text{eff}}$ | log $g$ | [Fe/H] | $\epsilon_{\text{micro}}$ |
|------------|------------------|---------|--------|--------------------------|
| BS 16934−002 | 4500             | 1.0     | $-2.8$ | 2.1                       |
| HD 122563 | 4600             | 1.1     | $-2.6$ | 2.2                       |

#### 3.2. Elements from Na to Zn

Standard analyses are applied to the equivalent widths listed in Table 2. The effects of hyperfine splitting on the Mn lines (McWilliam et al. 1995) are included in the analysis.

The Na abundances are determined from the weak Na i lines at 5682 and 5688 Å. While the Na i D lines are measurable in the spectrum of BS 16934−002, those in our spectrum of HD 122563 severely blend with interstellar absorption and could not be used for abundance analysis. The Na abundance of BS 16934−002, derived from the D lines, is about 0.5 dex higher than that obtained from the two weak lines mentioned above. This discrepancy is well explained by non-LTE (NLTE) effects studied by Takeda et al. (2003), who predicted the effect to be approximately 0.4 dex for cool giants with an equivalent width of 200 mA for the 5895 Å line.

We exclude the lines of the Mg triplet at 5170 Å (b lines) and at 3820 Å, because these very strong lines are inappropriate for precision abundance determinations. The Mg abundances determined from the 5528 and 5711 Å lines, which are detected in our new spectrum, agree very well with the results from the other four lines.

The Si abundances are determined from the four Si i lines at 4103, 5772, 5948, and 6155 Å. The very strong Si i 3905 Å line is excluded from the present analysis. Although the three lines in the red region are very weak ($W_r = 3−5$ mA in BS 16934−002), the agreement of the Si abundances from the individual lines is fairly good. In contrast to the Na, Mg, and Al abundance

#### Table 4

| Element | Species | Solar Abundance$^a$ | BS 16934−002 | HD 122563 |
|---------|---------|---------------------|--------------|-----------|
|         |         | (log ε)             | log ε [X/Fe] | N | σ   | log ε [X/Fe] | N | σ   |
| C       | CH      | 8.39                | 5.35         | $-0.27$ | ... | 0.17 | 5.45 | $-0.35$ | ... | 0.17 |
| N       | CN      | 7.78                | 5.65         | $+0.65$ | ... | 0.29 | 5.80 | $+0.61$ | ... | 0.29 |
| O       | O i     | 8.66                | 7.03         | $+1.14$ | 2   | 0.19 | 6.81 | $+0.74$ | 2   | 0.19 |
| Na      | Na i    | 6.17                | 4.20         | $+0.81$ | 2   | 0.13 | 3.39 | $-0.19$ | 2   | 0.13 |
| Mg      | Mg i    | 7.53                | 5.98         | $+1.23$ | 6   | 0.13 | 5.44 | $+0.49$ | 6   | 0.11 |
| Al      | Al i    | 6.37                | 3.76         | $+0.17$ | 1   | 0.19 | 3.38 | $-0.40$ | 1   | 0.18 |
| Si      | Si i    | 7.51                | 5.17         | $+0.44$ | 4   | 0.14 | 5.34 | $+0.41$ | 4   | 0.16 |
| Ca      | Ca i    | 6.31                | 3.89         | $+0.35$ | 22  | 0.13 | 3.93 | $+0.20$ | 20  | 0.11 |
| Sc      | Sc ii   | 3.05                | 0.87         | $+0.59$ | 14  | 0.24 | 0.57 | $+0.11$ | 14  | 0.23 |
| Ti      | Ti i    | 4.90                | 2.61         | $+0.48$ | 28  | 0.13 | 2.42 | $+0.11$ | 27  | 0.12 |
| Cr      | Cr i    | 5.64                | 2.67         | $-0.19$ | 11  | 0.11 | 2.57 | $-0.38$ | 13  | 0.10 |
| Mn      | Mn i    | 5.39                | 2.01         | $-0.61$ | 6   | 0.12 | 2.23 | $-0.57$ | 8   | 0.13 |
| Fe      | Fe i    | 7.45                | 4.68         | $-2.78_b$ | 130 | 0.20 | 4.86 | $-2.59_b$ | 214 | 0.20 |
| Fe      | Fe ii   | 7.45                | 4.67         | $-2.79_b$ | 20  | 0.19 | 4.87 | $-2.58_b$ | 20  | 0.19 |
| Co      | Co i    | 4.92                | 2.34         | $+0.19$ | 6   | 0.12 | 2.48 | $+0.15$ | 7   | 0.11 |
| Ni      | Ni i    | 6.23                | 3.38         | $-0.08$ | 16  | 0.12 | 3.66 | $+0.02$ | 15  | 0.11 |
| Zn      | Zn i    | 4.60                | 1.94         | $+0.11$ | 2   | 0.22 | 2.08 | $+0.06$ | 2   | 0.21 |
| Sr      | Sr ii   | 2.92                | $-1.22$      | $-1.36$ | 2   | 0.25 | 0.08 | $-0.30$ | 2   | 0.15 |
| Ba      | Ba ii   | 2.17                | $-2.29$      | $-1.69$ | 2   | 0.24 | $-1.69$ | $-1.28$ | 2   | 0.23 |

$^a$ Asplund et al. (2005).

$^b$ [Fe/H] values.
ratios relative to Fe, the [Si/Fe] ratio of BS 16934−002 agrees very well with that of HD 122563. While the abundance ratios of the iron-peak elements (Mn, Co, and Ni) are very similar for the two stars, significant excesses of the elements from Na to Ti, with the exception of Si, are found in BS 16934−002 as compared with HD 122563.

3.3. Neutron-Capture Elements

Both the light neutron-capture element Sr and the heavy neutron-capture element Ba are detected in our spectra of BS 16934−002. In the abundance measurement for Ba, the effects of hyperfine splitting are included, using the line list of McWilliam (1998) and assuming the isotope ratios found in the r-process component in solar system material (Arlandini et al. 1999). The heavy neutron-capture element ratio [Ba/Fe] of BS 16934−002, as well as that of HD 122563, is significantly underabundant relative to solar, as is usually found in very metal-poor stars. This implies no significant nucleosynthesis contribution from the s-process, although the complete abundance pattern of the heavy neutron-capture elements is not available for BS 16934−002.

The [Sr/Fe] abundance ratio of BS 16934−002 is more than 1 dex lower than that of HD 122563. However, given the large scatter of Sr abundances found in very metal-poor stars, the values of both stars are within the range of the Sr abundance distribution of previous observations. It should be noted that HD 122563 is a star that exhibits relatively large excesses of the light neutron-capture elements (Honda et al. 2006), while the Sr abundance ratio, as well as that of Ba, for BS 16934−002 is relatively low among stars with similar metallicity (Aoki et al. 2005). This suggests that BS 16934−002 formed from material that is not well mixed in the early Galaxy and might support our interpretation that the chemical composition of this object was basically determined by a single supernova event (§ 4).

3.4. Uncertainties

Random abundance errors in the standard analysis are estimated from the standard errors of the abundances derived from individual lines for each species. However, these values are sometimes unrealistically small when only a few lines are detected. For this reason, we adopt the larger of (1) the value for the listed species and (2) the standard error derived using the standard deviation of the abundance from individual Fe i lines and the number of lines used for the species as estimates of the random errors. Typical random errors are on the order of 0.1 dex.

We also tried another estimate of random errors using the standard deviation of the difference of the two equivalent width ($W$) measurements (4 mA) in § 2. We selected several Fe i lines around 4000 Å having $W$ of 20−150 mA and made abundance calculations, changing the $W$ by 4 mA. The effect on the derived Fe abundance distributes 0.07 to 0.11 dex, depending on $W$. This would support the above estimate of random errors from the standard errors of abundances derived from individual lines.
The random errors of carbon and nitrogen abundances are estimated by the fitting uncertainties for the CH and CN absorption bands, including the uncertainties of continuum placements. We adopted 0.1 and 0.2 dex as these errors for carbon and nitrogen abundances, respectively. We also reestimate the random errors for oxygen and sodium abundances, which are determined from weak absorption features and might be significantly affected by the uncertainty of the continuum level. We adopt the fitting uncertainties of 0.15 and 0.10 dex for the \([\text{O} n]_i\) and Na \(i\) lines, respectively.

We adopt estimates of errors arising from uncertainties of the atmospheric parameters from Aoki et al. (2005) for HD 122563, which were evaluated for \(\sigma(T_{\text{eff}}) = 100\, \text{K}\), \(\sigma(\log g) = 0.3\, \text{dex}\), and \(\sigma(V_{\text{micro}}) = 0.3\, \text{km}\, \text{s}^{-1}\). Finally, we derive the total uncertainty by adding in quadrature the individual errors and list them in Table 4.

4. DISCUSSION AND CONCLUDING REMARKS

4.1. Abundance Pattern of BS 16934–002

Abundance measurements of individual elements in metal-poor stars contain a variety of uncertainties, in addition to random measurement errors, due to errors in the adopted transition probabilities of spectral lines, errors in the adopted atmospheric parameters, and errors from uncertain NLTE effects. In order to avoid the influence of such uncertainties for the chemical abundances of BS 16934–002, we consider instead the abundance ratios (logarithmic differences) between BS 16934–002 and HD 122563. Although the uncertainty in the absolute abundances (e.g., \([\text{Fe}]/H\)) remains, the difference of the abundance patterns between these two stars should be little affected by NLTE effects and errors in the atmospheric parameters.

Figure 5 shows the difference in the abundance ratios between BS 16934–002 and HD 122563, on a logarithmic scale (i.e., \(\log [X/\text{H}]_{\text{BS}} - \log [X/\text{H}]_{\text{HD}}\)), as a function of atomic number. The abundance patterns of iron-peak elements in these two stars exhibit excellent agreement. One exception might be Cr; the \([\text{Cr}]/\text{Fe}\) value of BS 16934–002 is 0.2 dex higher than that of HD 122563.

By way of contrast, the abundance ratios of the elements from O to Ti in BS 16934–002 exhibit significant excesses with respect to Fe. The elements O, Na, Mg, Al, and Sc exhibit enhancements larger than +0.4 dex, while the excesses of Ca and Ti are smaller. An exception is Si; the Si abundance ratio of BS 16934–002 is almost identical to that of HD 122563. We note that the Ti abundances derived from Ti \(i\) and Ti \(ii\) yield similar differences between BS 16934–002 and HD 122563, suggesting that the difference is real. The enhancement of Na, an element having odd atomic number, is more significant than that of Mg. Another element with odd atomic number, Sc, also exhibits a larger excess than those of Ca and Ti.

The \(\alpha\)-elements in metal-deficient stars are believed to be produced primarily by core-collapse supernovae. The observed excesses of \(\alpha\)-elements in BS 16934–002 suggests the possible contribution of “special” core-collapse supernovae, which yield high \(\alpha\)-to-iron abundance ratios. There are two extremely metal-poor (EMP) CEMP-\(\alpha\) stars known, CS 22949-037 and CS 29498-043, which exhibit large enhancements of the \(\alpha\)-elements (Norris et al. 2001; Aoki et al. 2002; Depagne et al. 2002). Umeda & Nomoto (2003, 2005) interpreted the excesses of the \(\alpha\)-elements, as well as of C and N, in these objects as arising from so-called faint supernovae, for which they modeled the mixing after explosive nucleosynthesis and subsequent fallback onto the collapsed remnant (see also Tsujimoto & Shigeyama 2003). However, the C abundance of BS 16934–002 is not enhanced, in contrast to that of CS 22949-037 and CS 29498-043. Moreover, the total abundance of C and N in this star exhibits no significant excess (\(\Delta (\text{C} + \text{N})/\text{Fe} = +0.14\)). The normal C and N abundances, along with excesses of O and Mg, are unique characteristics of BS 16934–002, the first known AEMP star.

4.2. A Possible Interpretation of the Peculiar Composition of BS 16934–002

We have carried out a nucleosynthesis calculation for a supernova whose progenitor is a 40 \(M_{\odot}\), zero-metallicity (Population III) star that exploded with an explosion energy of 3 \times 10^{52} \text{ergs} (a hypernova whose explosion energy is larger than 1 \times 10^{52} \text{ergs}; e.g., Umeda & Nomoto 2005; Tominaga et al. 2007b). The high explosion energy is adopted to explain the large enhancement of C observed in BS 16934–002 (Umeda & Nomoto 2002). We assume the mixing-fallback model, where the explosively burned materials are mixed into the region of \(M_c = 2.67 - 8.06\, M_{\odot}\), and only a fraction, \(f = 0.025\), of the mixed material is ejected (the ejected Fe mass being 0.04 \(M_{\odot}\)) in order to approximately reproduce the overall abundance pattern of BS 16934–002 (Fig. 6, top, dot-dashed line). Such large-scale mixing and small amount of Fe ejection in the hypernova explosion can be realized in a jetlike explosion (Maeda & Nomoto 2003; Tominaga et al. 2007a). In this model, the electron fraction, \(Y_e\), in the explosive Si-burning layer is modified to \(Y_e = 0.5001\) and 0.4997 in the complete and incomplete Si-burning layers, respectively. This alteration of \(Y_e\) in the inner region can be realized by the interaction of inner materials with neutrinos emitted from the collapsed remnant (Fröhlich et al. 2006; N. Iwamoto et al. 2007, in preparation). However, note that Figure 6 (dot-dashed line) shows that our calculation predicts a large overabundance of carbon, which is not observed for BS 16934–002.

The observed ratios of \([\text{C}/\text{O}]/\odot \sim -1.4\) and \([\text{C}/\text{Mg}]/\odot \sim -1.5\) in BS 16934–002 are extremely low among known extremely metal-poor stars. We find that both ratios are \(-0.8\) or higher in our Population III supernova yields in the mass range 13–50 \(M_{\odot}\). Carbon is mainly produced by triple-\(\alpha\) reactions and is located above the O- and Mg-rich layers. Thus, one possible modification of the above model that might explain the lack of observed C-enhancement in BS 16934–002 is to consider the effects of significant mass loss from layers containing C-rich material from its massive progenitor during its evolution. This is an extension of the models of SN Ib and SN Ic, where the H and He
envelopes, respectively, have been removed, possibly through transfer across a binary. Binary-modulated stripping is suggested for the Type IIb SN 2001ig (Ryder et al. 2004) and has been given additional credibility by their subsequent discovery of a stellar-like object outliving the SN, which they believe to be the WR companion of the SN Ib/c (Ryder et al. 2006).

We calculated the internal abundance distribution of the 40 \( M_\odot \), Population III hypernova model and show the results in Figure 7. The loss of H-, He-, and CO-rich outer layers could be explained by common-envelope evolution in a close binary system and later by wind-mass loss during the He and CO star phases of the progenitor evolution. The solid line in the top panel of Figure 6 shows the abundance pattern calculated assuming significant mass ejection prior to explosion. We note here that the ejection of He- and C-rich layers may slightly affect the internal abundance distribution even if the H envelope is lost during or after the core He-burning phase. However, such an effect is not included in the model calculation here. The observed abundance ratios of [C/Mg] and [C/Fe] in BS 16934–002 are reproduced by this model. Here one important concern is that the C ejected before the explosion might be swept up by the shock wave and then possibly mixed with the supernova ejecta. The mixing process between the circumstellar matter (CSM) and supernova ejecta is still uncertain, and we here assume that the mixing with the nearby CSM is inefficient.

The observed excesses of elements with odd atomic numbers (N, Na, and Sc) are not explained by the above models. The excess of N ([N/Fe] = +0.65) could be a result of internal processes (e.g., the first dredge-up) during the evolution of BS 16934–002 itself. Indeed, a similar overabundance of N is also found in HD 122563, which has similar atmospheric parameters and is likely to be in a similar evolutionary stage. The underproduction of Sc in our supernova model is a problem in explaining the abundances of both BS 16934–002 and HD 122563 (see below for the latter object). This may be improved by using yields of nucleosynthesis in the explosion under low-density conditions (Umeda & Nomoto 2005) and/or a neutrino-driven nucleosynthesis (Fröhlich et al. 2006). Neutrino-driven nucleosynthesis may also account for the overproduction of Ti isotopes observed in BS 16934–002 (Pruet et al. 2005; Fröhlich et al. 2006). The overabundance of Na in BS 16934–002 is possibly explained by overshooting in the convective C-burning shell during the evolution of the massive star progenitor, as suggested by Iwamoto et al. (2005). The Na abundance ejected by a supernova is determined by the extent of the mixing and fallback regions. This is a possible reason for the fact that the Na overabundance is found in BS 16934–002, but is not seen in other objects.

Another important difference between BS 16934–002 and the two CEMP-\( \alpha \) stars CS 22949-037 and CS 29498-043 might be their iron abundances. BS 16934–002 has a significantly higher iron abundance ([Fe/H] = −2.8) than the other two stars (both of which have [Fe/H] ≤ −3.5). The EMP stars are considered to be formed from the ejecta of a single Population III or Population II supernova by supernova shock compression. The metallicities of EMP stars are determined by the ejected Fe mass, \( M(\text{Fe}) \), and the explosion energy \( E(E_{51}, \text{in units of 10}^{51} \text{ergs}) \) of

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13 Note that conventional models of a Population III star have no opacity source of heavy elements in the H envelope; hence, a radiation-driven wind does not operate, due to the low metallicity.
the parent supernova as follows (a supernova-induced star formation model; see Cioffi et al. 1988; Ryan et al. 1996; Shigeyama & Tsujimoto 1998; Umeda & Nomoto 2005; Tominaga et al. 2007b):

$$\frac{[\text{Fe/H}]}{[\text{X/H}]} \approx \frac{M(\text{Fe})/M(H)}{E_5} - C,$$

where $M(H)$ is the swept-up H mass, roughly proportional to the explosion energy $E$, and $C$ is a constant value as a function of the density and sound speed of the CSM.

In the context of a supernova-induced star formation model, CS 29498-043 ([Fe/H] = −3.75; Aoki et al. 2004) can be reproduced with constant $C = 0.8$ [a model with $M(\text{Fe}) = 0.001 M_{\odot}$ and $E_{51} = 1$, as shown in Fig. 9a of Umeda & Nomoto 2005]. If the same constant $C$ is applied to BS 16934 − 002, the predicted $[\text{Fe/H}]$ of BS 16934 − 002 would be $[\text{Fe/H}] = −3.7$, similar to CS 29498-043, because of the large explosion energy ($E_{51} = 30$), in spite of the large amount of Fe ejection [$M(\text{Fe}) = 0.04 M_{\odot}$]. Therefore, BS 16934 − 002 might have been formed from the ejecta of a Population II supernova that already had a higher metallicity, e.g., [Fe/H] ~ −3. However, the star formation process is affected by the uncertain distribution of the surrounding gas in the early Galaxy. Thus, there remains the possibility that Population II hypernovae form a portion of the [Fe/H] ~ −3 stars.

On the other hand, HD 122563 has a metallicity [Fe/H] = −2.6 and thus is a likely second- or later generation star (e.g., Tumlinson 2006). Therefore, we model the abundance pattern of HD 122563 using the yields integrated over a mass range of 11 − 50 $M_{\odot}$ with a Salpeter initial mass function, as shown in Figure 6 (bottom). The Population III supernova models employed are ($M_{\text{MS}}, E_{51}$) = (13, 1), (15, 1), (18, 1), (20, 10), (25, 10), (30, 20), (40, 30), and (50, 40) (Kobayashi et al. 2006; Nomoto et al. 2006; Tominaga et al. 2007b), where $M_{\text{MS}}$ is the main-sequence mass of the progenitor in solar masses. These models, with $M_{\text{MS}} > 20 M_{\odot}$, are assumed to explode as hypernovae with a higher initial metallicity, as indicated by the trend between the abundance scatter of the elements and the star-to-star scatter. Small variation in $T_{\text{eff}}$ is assumed, as in the model for BS 16934 − 002 discussed above. We note that the yields of Population III supernovae can be used even if HD 122563 is actually formed from the ejecta of Population II supernovae, because the explosive yield of a Population III model is not very different from that of a model with [Fe/H] = −3 (Tominaga et al. 2007b).

We have considered supernova explosions in an interacting binary system to explain the significant mass loss from the massive progenitor of BS 16934 − 002. Our interpretation, however, raises important questions as to why BS 16934 − 002 has such a peculiar composition and why only BS 16934 − 002 might require binarity in order to explain the observed abundance pattern. More investigations are clearly necessary to resolve these questions.

4.3. The Spread of Mg/Fe in Extremely Metal-poor Stars

The small spread of the observed abundance ratios of the α-elements (e.g., [Mg/Fe]) in very metal-poor stars has been emphasized by recent work (e.g., Cayrel et al. 2004; Arnone et al. 2005). The bulk of halo stars exhibit moderate overabundances of Mg, with star-to-star scatter as small as 0.1 dex, while much larger scatter is found for other elements, such as the neutron-capture elements. One possible interpretation of the small spread of the [Mg/Fe] ratios is that the Galactic halo was well mixed even in the earliest phases of its evolution (François et al. 2004). The Mg abundance of BS 16934 − 002 clearly deviates from the trend found in halo stars, suggesting that this star has a rather different nucleosynthesis history than the majority of halo objects. Other stars that exhibit departures from the abundance trend of the α-elements are the ADMP stars, with large underabundances of Mg (e.g., Ivans et al. 2003); these abundance patterns are not simply explained by any combination of the yields of Type Ia and II supernovae. Understanding the abundance patterns of AEMP stars, as well as those of ADMP stars, remains a challenge for studies of the nucleosynthesis processes that pertain to low-mass stars in the very early Galaxy.

Although recent studies based on high-resolution spectroscopy have revealed the chemical compositions of a significant number of EMP stars, much larger studies are required in order to better understand the observed abundance trends and the scatter about these trends in halo stars. In particular, for the lowest metallicity range (−4.0 ≤ [Fe/H] ≤ −3.5), at least two Mg-enhanced objects are known among the relatively small number of stars (10 − 20 objects) investigated to date, suggesting that a large scatter of the Mg abundance ratios may exist in this metallicity regime. The AEMP star BS 16934 − 002 might provide the first clues for developing an understanding of the relationship between the abundance scatter of α-elements in the lowest metallicity range and the clear trend found at relatively higher metallicity.

W. A. and K. N. are supported by a Grant-in-Aid for Science Research from JSPS (grant 152040109, 18104003). T. C. B. acknowledges partial funding for this work from grant AST 04-06784, as well as from grant PHY 02-16783, Physics Frontiers Center/Joint Institute for Nuclear Astrophysics (JINA), both awarded by the US National Science Foundation. K. N. has been supported in part by the Grant-in-Aid for Scientific Research (17030005, 17033002, and 18540231) and the 21st Century COE Program (QUEST) from the JSPS and MEXT of Japan. N. I. has been supported by the Grant-in-Aid for Young Scientists (B) (17740163). N. T. is supported through the JSPS Research Fellowship for Young Scientists. J. E. N. acknowledges support from the Australian Research Council under grant DP0342613.

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