The Astrophysical Journal, 569:L107–L110, 2002 April 20

EXTREMELY METAL-POOR STARS. IX. CS 22949-037 AND THE ROLE OF HYPERNOVAE

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Received 2002 February 5; accepted 2002 March 13; published 2002 March 21

ABSTRACT

We have obtained high-resolution spectra of the extremely metal-poor star CS 22949-037 ([Fe/H] = −3.79) in the region of the ultraviolet NH bands at 3360–3370 Å, which confirm our earlier report that it exhibits extreme nitrogen enhancement. We find [N/Fe] = 2.3 ± 0.4. The star is also known to have large relative overabundances, of order 0.5–1 dex, of carbon and the α-elements. This abundance pattern is not explained by any standard Galactic chemical enrichment model of which we are aware. The large N enhancement is, however, predicted by the zero heavy element, $M \gtrsim 200\ M_{\odot}$, hypernova models of Woosley & Weaver and Fryer, Woosley, & Heger. If the rotating models of Fryer et al. are relevant to the enrichment of CS 22949-037, one might expect it to possess a large overabundance of oxygen, with a mass fraction similar to or larger than that of nitrogen, and an [O I] λ6300.3 line strength of ∼2–8 mÅ.

Subject headings: nuclear reactions, nucleosynthesis, abundances — stars: abundances — stars: Population II

1. INTRODUCTION

The chemical abundances of the most metal-poor stars contain clues to conditions at the earliest times. As outlined in previous papers of this series (e.g., Norris, Ryan, & Beers 2001 and references therein), they constrain big bang nucleosynthesis, the nature of the first supernovae and other exotic objects (should they have existed), and the manner in which the ejecta from the first generations were incorporated into subsequent ones.

The red giant CS 22949-037 was discovered by Beers, Preston, & Shectman (1992), who reported [Fe/H] = −3.80, based on the strength of the Ca II K line on low-resolution spectra. McWilliam et al. (1995) obtained high-resolution spectra that firmly established the metal weakness and reported remarkable relative overabundances of carbon and the α-elements: [Fe/H] = −3.99, [C/Fe] = 0.88, [Mg/Fe] = 1.20, [Ca/Fe] = 0.90, and [Ti/Fe] = 0.53. Norris et al. (2001) confirmed this with high-resolution data of somewhat higher signal-to-noise ratio and found an extremely high relative nitrogen abundance—[N/Fe] = 2.7 ± 0.4—based on the violet CN band at 3883 Å. McWilliam et al. and Norris et al. discussed the enrichment of the material from which CS 22949-037 formed in terms of partial ejection of supernova mantles (see, e.g., Woosley & Weaver 1995)—but this offered no obvious explanation for the behavior of nitrogen. The latter authors noted that the only models that actually predict the large amounts of primary N that might explain the observed abundance are the massive (200–500 $M_{\odot}$), zero heavy element hypernovae first reported by Woosley & Weaver (1982).

Given the significance of the high nitrogen abundance of CS 22949-037, we sought to place the result on a firmer footing by obtaining spectra of the NH bands at 3360–3370 Å using the Anglo-Australian Telescope (AAT) and the Subaru Telescope, with a view to obtaining an independent estimate of its nitrogen abundance. We present our observations in § 2 and a model atmosphere abundance analysis in § 3. In § 4, we discuss the result in terms of the hypernova models of Woosley and coworkers.

2. OBSERVATIONAL MATERIAL

High-resolution spectra of CS 22949-037 and comparison stars were obtained with the University College London coudé echelle spectrograph on the AAT during 2001 August 24–25. The instrumental setup and data reduction techniques were similar to those described by Norris, Ryan, & Beers (1996, 2001) and will not be discussed here except to note that a 79 g mm^{-1} grating was employed, centered at 3363 Å, and that the detector was an EEV CCD having 13.5 μm pixels. Given the relative faintness of CS 22949-037, all data, including those of comparison stars, were obtained with the CCD binned by a factor of 4 in the dispersion direction, which resulted in pixels of width 0.08 Å. Spectra of ThAr and incandescent lamps were also taken for calibration purposes.

On August 24, CS 22949-037 was observed for a total integration time of 300 minutes, which resulted in 240 counts per 0.08 Å pixel at 3350 Å. During August 24–25, spectra were also obtained with the same configuration for the extremely metal-poor giants CD −38°245 ([Fe/H] = −3.98), CS 22885-096 ([Fe/H] = −3.66), and the archetypical metal-poor giant HD 122563 ([Fe/H] = −2.68), for which the corresponding counts were 600, 500, and 4500, respectively. The bright rotating B star μ^1 Sco was observed to define the order responses. After the spectra were reduced, they were slightly smoothed and divided by the highly smoothed spectrum of μ^1 Sco. From lines on the ThAr spectra reduced in the same manner, we estimate that the resolution of the final stellar spectra is 0.35 Å (FWHM).

TABLE 1

Atmospheric Parameters for Program Stars

Star (1)	T_{eff} (K) (2)	log *g* (3)	[Fe/H] (4)	[C/Fe] (5)	[O/Fe][a] (6)
CD −38°245	4850	1.80	−3.98	<0.00	0.60
HD 122563	4650	1.50	−2.68	−0.45	0.60
CS 22885-096	5050	1.90	−3.66	0.60	0.60
CS 22949-037	4900	1.70	−3.79	1.05	1.00
Sun	5780	4.44	0.00	0.00	0.00

[a] Assumed, not observed.

CS 22949-037 was also observed with the High-Dispersion Spectrograph of the Subaru Telescope on 2001 July 28. The EEV CCD detector covered the wavelength range 3070–3900 Å and was double-binned in the dispersion direction to give a pixel size of 0.02 Å. Total integration time was 165 minutes, which resulted in 1000 counts per 0.02 Å pixel at 3350 Å. Spectra of ThAr and incandescent lamps were also taken. The latter were, however, somewhat underexposed, and no attempt was made to flat-field the data. In presenting the spectrum in § 3, we have convolved the Subaru data with a Gaussian to produce an effective resolution of 0.35 Å (FWHM).

3. NITROGEN ABUNDANCES

Nitrogen abundances were determined by comparing model atmosphere synthetic spectra with the observed ones. The techniques employed in computing synthetic spectra have been presented in our earlier papers (e.g., Norris, Ryan, & Beers 1997, 2001) and will not be described in detail here. Suffice it to recall that all calculations were performed with codes that derive from the ATLAS formalism (see Cottrell & Norris 1978), that we assume line formation under local thermodynamic equilibrium, and that we used model atmospheres of Bell et al. (1976) and R. A. Bell (1983, private communication). Our line list contains the NH data and *gf*-values from Sneden (1974) and atomic lines kindly provided by R. A. Bell. Following Sneden, we adopted a dissociation energy of 3.21 eV for the NH molecule.[1]

Atmospheric parameters (excluding microturbulence, which is unimportant here), together with relative abundances of carbon, from Ryan, Norris, & Beers (1996) and Norris et al. (2001), are presented in columns (1)–(5) of Table 1, together with adopted solar values. Assumed oxygen abundances are given in column (6). As noted by Sneden (1973), nitrogen abundances determined from the NH features are insensitive to C and O abundances—as we confirmed by changing [C/H] and [O/H] by ±0.3 in the case of CS 22949-037 below.

Figure 1 compares synthetic spectra computed for the parameters in Table 1 with the observed spectrum of HD 122563 and with the solar spectrum of Kurucz et al. (1984; convolved to a resolution 0.35 Å FWHM). The thick line is the observed spectrum, while the three thin lines are model spectra separated by Δ[N/Fe] = 0.3, with the central [N/Fe]-value presented in the figure. The fit for the Sun is excellent, while the derived value for HD 122563 of [N/Fe] = 0.65 is somewhat smaller than the value of 1.2 reported by Sneden (1973), who used the model of Wolffram (1972) with $T_{\mathrm{eff}} = 4600$ K, $\log g = 1.2$, and [Fe/H] = −2.7—similar to values adopted here. We estimate that only 0.1 dex of the discrepancy can be attributed to atmospheric parameter differences and are unable to explain the remainder.

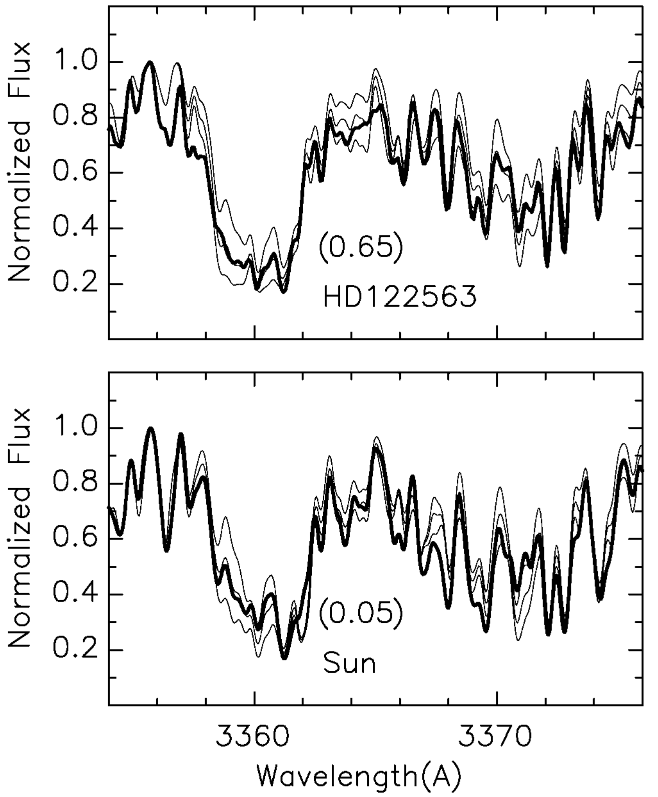

Fig. 1.—Comparison of observed (*thick line*) and synthetic (*thin lines*) spectra in the region of NH bands at 3360–3370 Å for the Sun and HD 122563. The three synthetic spectra are computed for nitrogen abundances that differ in steps of Δ[N/Fe] = 0.3, with the midvalue of [N/Fe] being given in parentheses in each panel.

Figure 2 shows fits for the extremely metal-poor red giants CD −38°245 and CS 22885-096. For CD −38°245, we find [N/Fe] = 1.2, which agrees reasonably well with the value of 1.6 reported by Bessell & Norris (1984). For CS 22885-096, we are not confident that NH has been detected and set [N/Fe] < 0.6.

Finally, in Figure 3 we present results for CS 22949-037 from the AAT and Subaru material. The NH bands are well defined in CS 22949-037 in both data sets. While for the AAT material the band is well contained on one echelle order, the Subaru orders are somewhat shorter and the data presented in Figure 3 come from contiguous orders. On each of these orders, the region near 3365 Å lies toward the edge of the order, and while the data have a higher signal-to-noise ratio than for the AAT material, we have less confidence in our ability to determine the continuum well. That said, the data are entirely consistent between the two data sets. For an assumed oxygen abundance of [O/Fe] = 1.0, we find [N/Fe] = 2.3 ± 0.4, which is consistent with the value of 2.7 ± 0.4 derived by Norris et al. (2001) from their analysis of the violet CN band. The present error estimate includes uncertainties of the fit in Figure 3 and the propagation of errors corresponding to $\Delta T_{\mathrm{eff}} = 100$ K and $\Delta \log g = 0.3$. The nitrogen abundance is insensitive to changes of Δ[C/H] = Δ[O/H] = 0.3.

4. DISCUSSION

The present investigation confirms that CS 22949-037 has an enormous overabundance of nitrogen. As noted by Norris

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[1] Had we adopted $D_{\mathrm{CN}} = 3.47$ eV, following R. L. Kurucz (2001; see http://cfaku5.harvard.edu/programs/atlas9/molec.datcd), the values of N/Fe for our program stars *relative to that of the Sun* would remain unchanged.

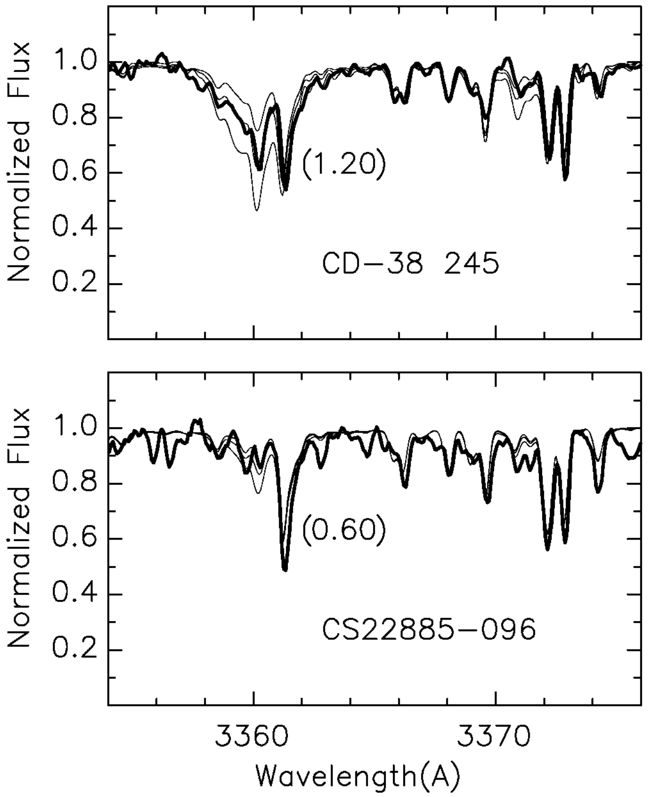

FIG. 2.—Comparison of observed (*thick line*) and synthetic (*thin lines*) spectra in the region of NH bands at 3360–3370 Å for CD −38°245 and CS 22885-096. As in Fig. 1, the three synthetic spectra differ in steps of Δ[N/Fe] = 0.3, with the midvalue of [N/Fe] being given in parentheses in each panel.

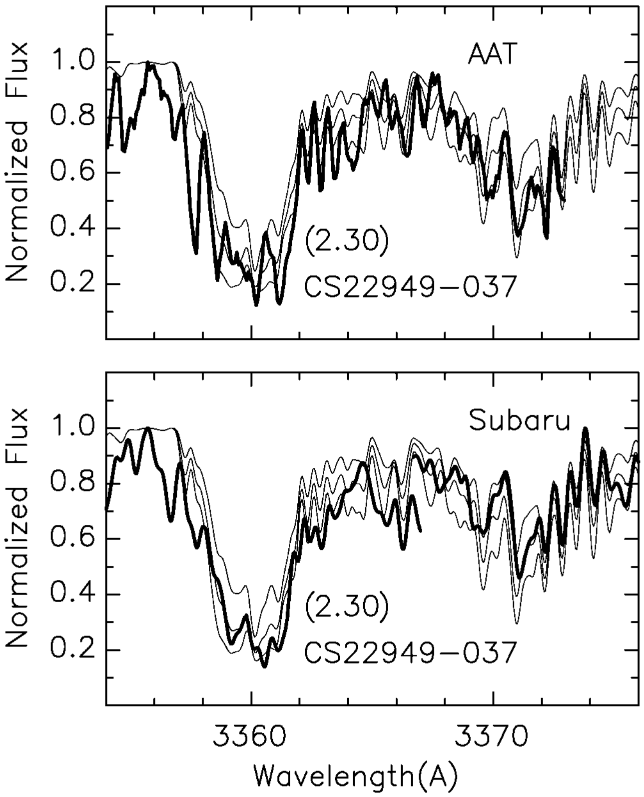

FIG. 3.—Comparison of observed (*thick line*) and synthetic (*thin lines*) spectra in the region of NH bands at 3360–3370 Å for CS 22949-037 from the AAT (*upper panel*) and Subaru (*lower panel*). The three synthetic spectra differ in steps of Δ[N/Fe] = 0.3, with the midvalue of [N/Fe] being given in parentheses in each panel.

et al. (2001), none of the existing standard models of Galactic chemical enrichment (GCE), which include stars only less massive than 100 $M_{\odot}$, predict such an effect. The standard GCE models of Timmes, Woosley, & Weaver (1995), for example, are predicated on nitrogen being produced as a secondary element in massive stars and predict substantially subsolar N/Fe ratios at lowest abundance. Suggested ways of producing supersolar values of N/Fe include rotationally driven mixing (e.g., Maeder 1997), convective overshoot, or supermixing (e.g., Timmes et al. 1995), and the class of zero heavy element hypernovae (massive pair instability supernovae) first discussed by Woosley & Weaver (1982). As noted by Carr, Bond, & Arnett (1984), the essential feature of these very massive ($M \gtrsim 200\ M_{\odot}$) objects is their potential to "pass carbon and oxygen from the helium-burning core through the hydrogen-burning shell, in such a way that it is CNO processed to nitrogen before entering the hydrogen envelope."

Also of particular interest is the recent work of Fryer, Woosley, & Heger (2001), who consider the evolution of rotating zero heavy element objects of mass 250 and 300 $M_{\odot}$. They find that primary N is produced once traces of C and O from the He-burning core are mixed out to the H-burning shell by meridional circulation. In the envelope of the 250 $M_{\odot}$ object, this leads to mass fractions of C, N, and O of 0.0026, 0.078, and 0.080, respectively, while for the 300 $M_{\odot}$ case the corresponding fractions are 0.00033, 0.013, and 0.057. For the more massive object, they also report a mass fraction of Mg of 0.00395. Fryer et al. emphasize, however, that these estimates are "sensitive to the highly uncertain physics of convection and rotational instabilities." Although the 300 $M_{\odot}$ model collapsed to a black hole, and hence did not enrich the interstellar medium, we nevertheless include it in our discussion. Given the uncertainties, the 300 $M_{\odot}$ model provides a useful indication of what nucleosynthesis might be possible, and it may yet prove feasible to remove part of the envelope prior to collapse, for example, in a stellar wind, or as the result of pulsations.

Further work on the yields of this type of object are clearly needed for comparison with spectroscopic abundances such as those reported here. Given that CS 22949-037 represents one of the unbiased set of six stars having [Fe/H] < −3.5 for which high-resolution analysis exists (Norris et al. 2001), it may represent a not uncommon phenomenon at the earliest times. Metal abundances in the envelopes of the Fryer et al. models are dominated by N and/or O, and it is interesting to see whether such models can explain the high C and N abundances of CS 22949-037. We show in Table 2 that the N/C ratio of the 250 and 300 $M_{\odot}$ models is an order of magnitude larger than even the high value observed in CS 22949-037. In contrast to results from lower mass models where nitrogen production is below

TABLE 2

ABUNDANCES IN MODELS AND OBSERVATIONS

Ratio (1)	250 $M_{\odot}$ (2)	300 $M_{\odot}$ (3)	CS 22949-037 (4)
log (N/C)	1.41	1.52	0.57
log (Mg/N)	...	−0.74	−1.42
log (O/N)	−0.05	0.59	...
[O/Fe][a]	1.34	1.98	...
[O/Fe][b]	2.10	2.85	...

[a] Assuming [N/Fe] = 2.30 and log (O/N) as modeled.

[b] Assuming [C/Fe] = 1.05 and log (O/C) as modeled.

observed values, the two hypernova models far surpass it. That is, hypernovae could be capable of generating the large quantities of N observed in CS 22949-037. The *lower* N/C ratios observed in stars require that not all hypernovae convert as much of their carbon to nitrogen as these particular models do or that the N-rich ejecta of such objects is diluted with N-poor but nevertheless metal-enriched material before incorporation into Population II stars. Hypernova models, or at least the more massive ones, are also able to produce Mg in quantity. The 300 $M_\odot$ model gives an Mg abundance only a factor of 5 below that of N, which is 5 times more than required to match the Mg/N ratio in CS 22949-037.

While we have emphasized the possible role of massive objects, we should also recall the caveat in the work of Heger, Woosley, & Waters (2000), who report that the shallow entropy gradient for stars of lower mass (e.g., 60 $M_\odot$) can also lead to (relatively moderate) envelope nitrogen enhancement by the mechanism discussed by Woosley & Weaver (1982). It remains to be seen whether such low-mass objects, with or without rotation, could have produced the nitrogen and α-element enhancements seen in CS 22949-037.

It is also worth comparing the abundances of the heavier elements in CS 22949-037 with those of the nonrotating hypernovae of Heger & Woosley (2002). Among other findings, they predict a strong "odd-even" effect, with elements having odd nuclear charge underproduced relative to neighboring ones with even charge. They also report zero production of the heavy neutron-capture elements. Neither of these effects is evident for CS 22949-037 (McWilliam et al. 1995; Norris et al. 2001), which has relative abundances for the iron peak and heavier elements that do not distinguish it from other extremely metal-poor stars. It then remains to be seen whether the results of Heger & Woosley are sensitive to rotation. One should also bear in mind that CS 22949-037 may have formed from material enriched not only by ejecta from zero heavy element hypernovae but also from less massive objects.

In spite of these caveats, if the Fryer et al. simulations are relevant to the process that enriched the material from which CS 22949-037 formed, one may use them to make an interesting prediction. In the models of Fryer et al., one sees relatively small C production accompanied by larger and similar mass fractions of N and O. It thus appears that, while large amounts of C have been converted to N as C, O-rich material passes through the H-burning shell, the same is not true for O, which remains largely unprocessed. The possibility therefore exists that in CS 22949-037 the mass fraction of oxygen may be of the same order as, or greater than, that of nitrogen. A. Heger (2002, private communication) also advises that the O yields of their models could considerably exceed even the high values inferred from their envelopes, depending on how much of the O-rich core is also ejected, carrying with it additional products of nucleosynthesis.

For the N and O mass fractions in the models of Fryer et al., one might then expect [O/Fe] = 1.3–2.0 in CS 22949-037 (see Table 2). Even higher [O/Fe]-values could be inferred from the C and O mass fractions, but as C is only a minor constituent in the envelope, being the leftovers from the conversion of C to N, its mass fraction is considerably more uncertain. (We note for completeness that our determinations of both [C/Fe] and [N/Fe] for CS 22949-037 remain unchanged if we adopt [O/Fe] = 2.0.) A model atmosphere analysis for CS 22949-037 indicates that the forbidden neutral oxygen line [O I] λ6300.3 would have an equivalent width of ∼2–8 mÅ over this [O/Fe] range. Finally, given that the ultraviolet OH lines near 3140 Å are present in CD −38°245 ([Fe/H] = −3.98), for which Bessell & Norris (1987) report [O/Fe] = 1.3, one might also hope to observe the UV OH lines in CS 22949-037.[2] On the other hand, since CS 22949-037 is relatively faint, with $B = 15.1$, this might be a difficult observation even for 8–10 m class telescopes.[3]

We are grateful to the director and staff of the Anglo-Australian Observatory and the Australian Time Allocation Committee for providing facilities used in our study. This Letter is based in part on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan. We gratefully acknowledge helpful discussions with A. Heger and S. E. Woosley. T. C. B. acknowledges support of NSF grants AST 95-29454, AST 00-98549, and AST 00-98508. S. G. R. was supported by PPARC grant PPA/O/S/1998/00658.

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[2] As we prepared this work for publication, word reached us that a measurement had subsequently been made of oxygen features in CS 22949-037 by R. Cayrel and coworkers. We await details of that work with interest.

[3] The present spectra have insufficient signal-to-noise ratio to address this question.

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