Carnegie Observatories Astrophysics Series, Vol. 4:
Origin and Evolution of the Elements, 2004
ed. A. McWilliam and M. Rauch (Pasadena: Carnegie Observatories,
http://www.ociw.edu/ociw/symposia/series/symposium4/proceedings.html)

A New Population of Old Stars

I. I. IVANS[1], C. SNEDEN[2], C. R. JAMES[3], G. W. PRESTON[4],
J. P. FULBRIGHT[4], P. A. HÖFLICH[2], B. W. CARNEY[5], and J. C. WHEELER[2]
(1) California Institute of Technology, Pasadena, CA, USA
(2) The University of Texas at Austin and McDonald Observatory, TX, USA
(3) Sam Houston State University, Huntsville, TX, USA
(4) The Observatories of the Carnegie Institution of Washington, Pasadena, CA, USA
(5) University of North Carolina, Chapel Hill, NC, USA

Abstract

We report the results of a coherent study of three chemically anomalous metal-poor ([Fe/H] $\sim$ –2) stars. These objects exhibit unusually low abundances of Mg, Si, Ca (α-elements) and Sr, Y, and Ba (neutron-capture elements). Our analyses confirm and expand upon earlier reports of atypical abundances in BD+80 245, G4-36, and CS22966-043. We also find that the latter two stars exhibit enhanced abundances of Cr, Mn, Ni, and Zn (iron-peak elements), along with what appears to be large abundances of Ga, with respect to the abundance of iron. Comparing the chemical abundances of these stars to supernova model yields, we derive supernovae ratios of Type Ia versus Type II events in the range of $0.6 \leq (N_{Ia}/N_{II})_{NewPop} \leq 1.3$. Whereas, for the Sun, we derive supernovae ratios in good agreement with those found in the literature: $0.18 \pm 0.01 < (N_{Ia}/N_{II})_{\odot} < 0.25 \pm 0.06$. Given the relatively low metallicity and high (N_{Ia}/N_{II}) rations of the low-α stars studied here, these objects may have witnessed, or been born from material produced in the yields of the earliest supernova Type Ia events.

1.1 Introduction & Background

At early Galactic times, the main contributors to the chemical enrichment of the interstellar medium were presumably the most massive and shortest-lived stars. Their resulting core collapse supernovae explosions of Type II ("SNe II"; and to a lesser extent, SNe Ib and SNe Ic), enriched the medium in α-elements (eg. 0, Ne, Mg, Si, Ca) and odd-Z elements (eg. Na, Al, P), among others. Neutron-rich sites, presumably associated with the core collapse supernovae, contributed additional elements produced in rapid neutron-capture nucleosynthesis ("*r*-process"; eg. Eu). Evolving more slowly, lower mass stars began contributing their ejecta to the medium at later Galactic times, first adding those isotopes produced in slow neutron-capture nucleosynthesis ("*s*-process"; eg. Sr, Ba) and then later, Fe-peak nuclei via supernovae Type Ia ("SNe Ia") explosions.

The stage in Galactic evolution at which SNe Ia began to contribute is not known precisely. However, an overall Galactic trend in the lowering of the [α/Fe]-ratio at about [Fe/H] $\simeq$ –1 is associated with the increase in Fe due to SNe Ia contributions (eg. Tinsley 1979, Pagel & Tautvaisiene 1995, their Figure 3).

A number of studies have discovered stars of intermediately low metallicities that also possess relatively low [α/Fe], [Na/Fe], and/or neutron-capture element abundance ratios when compared to stars of comparable metallicities (with differences in the range of 0.1

– 0.6 dex) . The studies include the outer halo star BD+6 855 ([Fe/H] $\simeq$ –0.7; Carney & Latham 1985); a sample of high velocity stars (–1.3 < [Fe/H] < –0.4; Nissen & Schuster 1997; "NS97"); the outer halo common proper motion pair HD134439/40 ([Fe/H] $\simeq$ –1.5; King 1997); and the relatively young outer halo clusters Pal 12 and Rup 106 ([Fe/H] $\simeq$ –1 and –1.4, respectively; Brown et al 1997). The abundances and kinematics of all of these objects are consistent with the idea of accretion events in the outer halo.

Studies encompassing larger samples of halo stars have found that the average [α/Fe]-ratio is lower for stars with higher-than-average space velocities (Fulbright 2002) and for stars with orbits that take them to the outer halo (Stephens & Boesgaard 2002). These kinematically extreme stars may have formed at large distances from the Galactic center in either localized star-forming regions or in proto-galactic fragments which were later assimilated into the Milky Way.

Recently, there have been a few serendipitous discoveries of low-metallicity stars ([Fe/H] $\simeq$ –2) that exhibit anomalously low abundances of α-elements (in some cases, over 1 dex lower than is exhibited in halo stars of comparable metallicities that follow the general trend of an overall α-enhancement). BD+80 245 (Carney et al 1997), G4-36 (James 1998, 2000), and BPS CS22966-043 (Preston & Sneden 2000) all exhibit similar under-abundances in their [α/Fe]-ratios and are also deficient in the abundance of neutron-capture elements. In our analysis, we studied these stars as a group, expanding the number of elemental abundances, and explored the idea that the elemental abundance ratio diminishments in these stars are the results of iron enhancements from SNe Ia contributions.

1.2 Key Abundance Results

In our analysis, we confirm the previous reports of the unusual nature of these stars, and expand the number of elements studied. All three objects possess anomalously low light-α- and odd-Z element abundances with respect to stars of comparable metallicities, as well as low abundances of Sr and Ba (by almost 2 dex in the case of BD+80 245). We find, however, that the low-α stars do not share the same behavior in the abundances of Fe-peak elements. BD+80 245 exhibits slightly low Fe-peak abundances with respect to iron (0.2 – 0.3 dex), whereas G4-36 and CS22966-043 are significantly enhanced (up to 0.5 – 0.7 dex) relative to the scaled solar metallicity. Table 1.1 displays the abundances we derived for our stars, as well as the mean of the halo in the metallicity range of –1.75 < [Fe/H] < –2.25. As can be seen in this table, as well as in Figure 1.1, the elemental abundances of our low-α stars are very dissimilar to those found in the general halo population. Further details of the observational material and abundance analysis are described in Ivans et al (2003).

1.3 Comparisons to Supernova Model Yields

The iron contribution from SNe Ia yields to Galactic evolution is observed in the trend of the lowering of the [α/Fe]-ratio at [Fe/H] $\simeq$ –1 (Tinsley 1979; Pagel & Tautvaisiene 1995, their Figure 3). In our study, we attempted to match the abundances of our unusual low-α stars to various yields from supernova models in the literature by making the assumption that the total abundance of some element (X) observed in these stars is the result of a mix of SNe Ia and SNe II contributions:

$$\mathcal{R}_{obs} \equiv \frac{M_\star(X)}{M_\star(Fe)} = \frac{N_{Ia}M_{Ia}(X)+N_{II}M_{II}(X)}{N_{Ia}M_{Ia}(Fe)+N_{II}M_{II}(Fe)}, \quad (1.1)$$

Table 1.1. *Abundance Results and Comparison to Halo Field Means*

Ratio	Halo Field	BD+80 245	G4-36	CS22966-043
$[Fe/H]_{I}$		–2.09 (0.11)	–1.93 (0.11)	–1.91 (0.15)
$[Fe/H]_{II}$		–2.04 (0.11)	–1.95 (0.11)	–1.91 (0.16)
$[X/Fe]$				
Na	+0.03 (σ=0.38)	–0.41 (0.05)	–0.28 (0.08)	–0.64 (0.16)
Mg	+0.37 (σ=0.13)	–0.22 (0.11)	–0.19 (0.14)	–0.65 (0.15)
Al	–0.10 (σ=0.45)	–1.33 (0.15)	–1.44 (0.15)	<–0.9
Si	+0.42 (σ=0.15)	–0.11 (0.15)	–0.26 (0.15)	–0.97
Ca	+0.31 (σ=0.13)	–0.18 (0.13)	–0.21 (0.11)	–0.24
Sc	+0.11 (σ=0.26)	–0.42 (0.10)	–0.76 (0.05)	–0.76 (0.05)
Ti	+0.26 (σ=0.16)	–0.30 (0.05)	+0.54 (0.07)	+0.60 (0.10)
V	–0.06 (σ=0.23)	–0.39 (0.10)	+0.32 (0.05)	<+1.2
Cr	–0.06 (σ=0.10)	+0.01 (0.06)	+0.41 (0.06)	+0.34 (0.06)
Mn	–0.28 (σ=0.16)	–0.26 (0.08)	+0.37 (0.09)	+0.41 (0.12)
Co	–0.27 (σ=0.39)	–0.18 (0.10)	+0.33 (0.20)	<+0.5
Ni	+0.00 (σ=0.14)	–0.09 (0.09)	+0.48 (0.11)	+0.54 (0.15)
Cu	–0.63 (σ=0.15)	<–1.0	<–0.7	<+1.5
Zn	+0.08 (σ=0.08)	–0.42 (0.15)	+1.00 (0.05)	+1.09 (0.15)
Ga	···(a)	–0.30 (0.10)	+0.58 (0.10)	+1.75 (0.20)
Sr	+0.17 (σ=0.43)	–0.85 (0.10)	–0.65 (0.26)	–0.99 (0.05)
Y	–0.13 (σ=0.20)	<–1.2	<–0.7	<+0.6
Ba	–0.01 (σ=0.32)	–1.89 (0.15)	–0.72 (0.13)	<–0.6
La	+0.07 (σ=0.30)	–0.82 (0.15)	<+1.4	<+3.4
Eu	+0.41 (σ=0.26)	–0.64 (0.18)	<+0.4	<+1.2

Additional Note:
(a) Ga abundances for metal-poor stars do not exist in the literature.

from which we can derive the following:

$$\frac{N_{Ia}}{N_{II}} = \frac{M_{II}(X) - \mathcal{R}_{obs}\, M_{II}(Fe)}{\mathcal{R}_{obs}\, M_{Ia}(Fe) - M_{Ia}(X)} \tag{1.2}$$

where $\mathcal{R}_{obs} \equiv M_{\star}(X)/M_{\star}(Fe)$ denotes the ratio of the mass of element (X) to the mass of iron in our star, $M_{Ia}(X)$ and $M_{II}(X)$ denote the mass of element (X) ejected from SNe Ia and SNe II, and N_{Ia}/N_{II} represents the ratio of the number of SNe Ia to SNe II events that fit the observations and the synthesized mass of elements (X) and iron from the model yields.

We employed yields from models representing SNe II from massive stars in the range of 10–50 $M_{\odot}$ and those representing SNe Ia resulting from thermonuclear explosions of electron-degenerate cores such as those found in white dwarfs in close binary systems. We used the yield compilation of Iwamoto et al (1999; their Table 3), which includes SNe II yields based on calculations by Nomoto & Hashimoto (1988), Hashimoto et al (1989, 1996) and Thielemann et al (1996), and SNe Ia yields for seven models based on calculations by the Nomoto et al (1984), Thielemann et al (1986), Hix & Thielemann (1996). We also

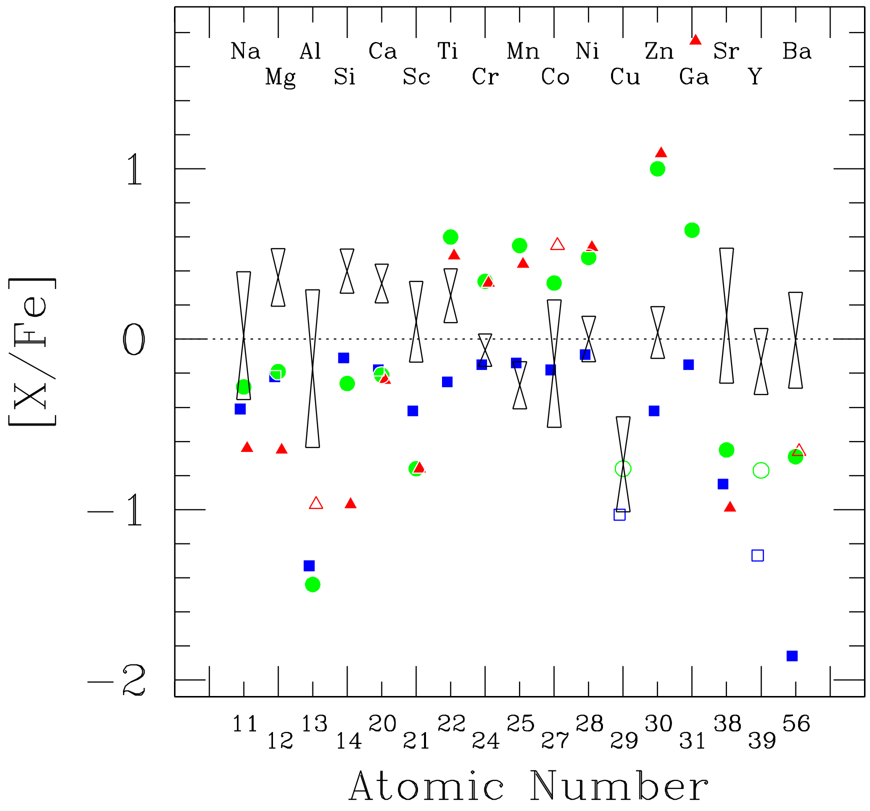

Fig. 1.1. Elemental abundances from Table 1.1 for BD+80 245 (blue square), G4-36 (green circle) and CS22966-043 (green triangle). Abundances of halo stars of comparable metallicities (–1.75 < [Fe/H] < –2.25) are denoted by (⋈, centered on and extending 1-σ from the mean value). Strict upper limits are denoted by hollow symbols.

expanded the SNe Ia model yields we employed to include a suite of 45 models produced in calculations made by Höflich et al (1995, 1998, 2002), Höflich & Khokhlov (1996), and Domínguez et al (2001).

We first tested the results of the model yields against the observed solar abundance ratios. Using solar abundances of O, Na, Mg, Al, and Si from the compilation of Anders & Grevesse (1989), and the SNe Ia yields tabulated in Table 3 of Iwamoto et al, we derived a value of $(N_{Ia}/N_{II})_{\odot}$ = 0.24 $\pm$ 0.07. We then explored the differences that resulted from revising the Anders & Grevesse recommendation of log ϵ(O) = 8.93 to 8.80, the O abundance recommended by Reetz (1999), 8.74 by Holweger (2001), and 8.69 by Allende Prieto et al

(2001). These O abundance revisions resulted in raising both the $(N_{Ia}/N_{II})_{\odot}$, and associated σ to 0.28 ± 0.07, 0.29 ± 0.09, and 0.31 ± 0.11, respectively. Since we have no way to determine whether the increase in scatter resulting from the revised O abundances are due to errors in the abundances or to errors in the model yields, we dropped [O/Fe] from our (N_{Ia}/N_{II}) determinations, recognizing that the evidence for this decision is not entirely compelling. The supernovae ratio we derive from $[(\mathrm{Na,Mg,Al,Si})/\mathrm{Fe}]_{\odot}$ using this set of SNe Ia model yields is $(N_{Ia}/N_{II}) = 0.25 \pm 0.06$.

For other elements, the simple prescription fails. As seen in previous studies (see eg. Timmes et al 1995, and references therein), the observations of the abundances of N, Sc, Ti, V, Co, Ni, Cu, and Zn, among others, show poor agreement with the predictions by supernova models. A better understanding of supernovae contributions to nucleosynthesis is required in order to explain why no combination of supernova models is able to satisfactorily reproduce the observations of the abundances of these elements.

As an additional "sanity check", we also derived the ratio of SNe Ia to SNe II required to explain the observed abundances of CS22892-052, a metal-poor ([Fe/H] $\simeq$ –3.1) *r*-process-rich star believed to have witnessed one (or only a few) previous supernova(e) event(s) of Type II only (see eg. Sneden et al 2003, and references therein). The SNe Ia to SNe II ratio we derive from the published ratios of [(Na,Mg,Si)/Fe] is $(N_{Ia}/N_{II})_{CS22892\text{–}052} = 0.01 \pm 0.11$, a sensible result. In our application of the method to stars other than the Sun, we found that the results for Al were not well-matched to those from Na and the α-elements. Discussion in the literature has noted that the abundance of light-odd-Z neutron-rich elements are sensitive to the neutron excess and errors in the models can be large. Rederiving the supernovae ratio for the Sun, without including the Al abundance, we find $(N_{Ia}/N_{II})_{\odot} = 0.22 \pm 0.05$. Employing the expanded suite of models by the Höflich group, we derive similar results: $(N_{Ia}/N_{II})_{\odot} = 0.18 \pm 0.01$.

The ratio of contributing supernovae types we derive for the Sun are in good agreement with literature values of Galactic ratios of SNe Ia to SNe II events, as shown in Table 1.2. For the average abundances listed in Table 1.1, we derive $(N_{Ia}/N_{II})_{Halo} = 0.09 \pm 0.11$ (employing yields tabulated in Iwamoto et al) or ± 0.10 (employing the Höflich group SNe Ia yields). However, the ratios we derive for the low-α stars of this study (as well as some of the stars discussed in §1.1), require significantly greater amounts of SNe Ia material.

1.3.1 Results from SNe Ib, SNe Ic, and High Energy SNe II ("Hypernovae") Yields

Employing the yields of hypernovae models of varying mass and energy developed by Umeda & Nomoto (2002) in place of the SNe II model calculations tabulated by Iwamoto et al, we rederived the (N_{Ia}/N_{II}) ratios for our low-α stars. In no instance does the variation in derived (N_{Ia}/N_{II}) improve over those of standard SNe II. We also rederived the (N_{Ia}/N_{II}) ratios for our low-α stars employing yields of the full range of SNe Ib and SNe Ic models calculated by Woosley et al (1995). We attempted to employ their yields to our abundance ratios both by treating the SNe Ib and SNe Ic models as alternatives to the SNe II yields, and by treating them as alternatives to the SNe Ia yields. In neither case could we obtain satisfactory agreement among the abundances for any of our stars. We find that the unusual abundances of our stellar trio cannot be explained by the hypernova models of Umeda & Nomoto or by the SNe Ib or SNe Ic models of Woosley et al.

Table 1.2. (N_{Ia}/N_{II}) *Estimates*

Star	(N_{Ia}/N_{II})	[X/Fe]	Source
Sun	0.25 ± 0.06	Na, Mg, Al, Si	(1)
	0.22 ± 0.05	Na, Mg, Si	(1)
	0.18 ± 0.01	Na, Mg, Si	(2)
	0.12 – 0.36	···	(3)
	0.15		(4)
	0.187 – 0.257		(5)
CS22892-052	0.01 ± 0.11	Na, Mg, Si	(1)
	0.01 ± 0.10	Na, Mg, Si	(2)
Halo [Fe/H] $\simeq$ –2	0.09 ± 0.11	Na, Mg	(1)
	0.09 ± 0.10	Na, Mg	(2)
BD+80 245	0.58 ± 0.21	Na, Mg, Si	(1)
	0.47 ± 0.21	Na, Mg, Si	(2)
G4-36	0.43 ± 0.10	Na, Mg	(1)
	0.45 ± 0.12	Na, Mg, Si	(2)
CS22966-043	1.29 ± 0.08	Na, Mg, Si	(1)
	1.22 ± 0.01	Na, Mg, Si	(2)
NS97 Low-α	0.23 ± 0.11	Na, Mg, Si	(1)
	0.20 ± 0.10	Na, Mg, Si	(2)
NS97 Other Halo	0.08 ± 0.03	Na, Mg, Si	(1)
	0.07 ± 0.03	Na, Mg, Si	(2)
Pal 12	0.38 ± 0.22	Na, Mg, Si	(1)
	0.29 ± 0.18	Na, Mg, Si	(2)
Rup 106	0.39 ± 0.32	Na, Mg, Si	(1)
	0.34 ± 0.31	Na, Mg, Si	(2)
HD134439/40	0.41 ± 0.18	Na, Mg, Si	(1)
	0.34 ± 0.19	Na, Mg, Si	(2)

Table Notes and References:
(1) Derived from fits of stellar abundances to published SNe II and SNe Ia yields (as tabulated in Iwamoto et al 1999; their Table 3).
(2) Derived from fits of stellar abundances to published SNe II (as tabulated in Iwamoto et al 1999; their Table 3) and SNe Ia yields (from the Höflich group).
(3) van den Bergh & Tammann (1991)
(4) Tsujimoto et al (1995)
(5) Iwamoto et al (1995)

1.4 Alternative Explanations?

We explored the possibility that the source of the abundance anomalies in our stars may be the result of something other than SNe Ia-enhanced material. The details are presented in Ivans et al (2003) but, in summary, we find we cannot explain the abundances by invoking binarity and mass transfer; formation from AGB-enriched material; or chemically stratified atmospheres. The supernovae ratios we derived do not allow us to distinguish between the possibility that our stars formed from material enriched in SNe Ia yields and the possibility that our stars were born from much less chemically enriched material at earlier times and nearby SNe Ia events occurring at later times deposited Fe nuclei on the surfaces of our stars. However, the ratios of the abundances of the neutron-capture elements suggest that the latter possibility is less likely.

While it is possible that the atmospheres do not represent the interstellar material out of which they were born, and instead exhibit the effects of pollution from some other source, no potential contributor has been observed that displays abundances similar to those we derive.

1.5 Summary & Conclusions

Evidence of chemical substructure in the Galactic halo is seen in the elemental abundances of BD+80 245, G4-36, and CS22966-043. These stars were all serendipitously discovered as having low α-element and neutron-capture element abundances in the context of previous studies. In our study, we confirm the earlier reports and expand the number of elements for which abundances have been derived in these stars. We find that the mean abundance ratio for [(Mg,Si,Ca)/Fe] is ~ 0.7 dex below the mean of halo stars of comparable metallicities and that the mean abundance ratio for [(Sr,Ba)/Fe] is $\sim$ a full dex below the halo mean.

Our low-α stars do not display uniform abundances of the Fe-peak nuclei with respect to the abundance of iron. BD+80 245 exhibits diminishments whereas G4-36 and CS22966-043 present mild to pronounced over-abundances of these elements. The latter two stars require such large Ga enhancements to synthesize the observed spectra that it is possible, for the first time, to report Ga abundances in any metal-poor star.

We explore the idea that the elemental abundance ratios in these stars can be explained by iron enhancements from SNe Ia contributions. We derive $0.18 \pm 0.01 < (N_{Ia}/N_{II}) < 0.25 \pm 0.06$ for the Sun, which is in good agreement with values found in the literature for Galactic ratios of supernovae Type II to Type Ia events. The results for our low-α trio confirm the idea that the low α- and low neutron-capture element abundances can be explained by a larger contribution of SNe Ia yields than went into the average halo star: $0.6 \leq < (N_{Ia}/N_{II}) < 1.3$. Thus, given the metallicities of our stars, it would appear that BD+80 245, G4-36, and CS22966-043 may have formed from the material polluted by the earliest of SNe Ia events. However, our derivations were limited to a small subset of the observed abundances. The unusual abundance ratios of Ti, Cr, Mn, Ni, and Zn (among other elements) cannot be modeled using existing supernova model yields. Additional questions which we would like to explore are the determination of the SNe Ia progenitors, and whether the progenitors or scenarios have changed over Galactic timescales. To our knowledge, an identification or determination of SNe Ia progenitors based on the observed chemical abundances of metal-poor stars does not exist in the literature. The three low-α stars represent a non-negligible part of early Galactic nucleosynthesis, yet are not explained by current Galactic evolution models.

1.6 Acknowledgments

Research by III is currently supported by NASA through Hubble Fellowship grant HST-HF-01151.01-A from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract 5-26555.

I also thank the organizers of the Carnegie Observatories Symposium on the Origin and Evolution of the Elements for making this meeting such an interesting and fruitful one.

References

Allende Prieto, C., Lambert, D. & Asplund, M. 2001, ApJ, 556, L63
Anders, E. & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Brown, J. A., Wallerstein, G. & Zucker, D. 1997, AJ, 114, 180
Carney, B. W. & Latham, D. W. 1985, ApJ, 298, 803
Carney, B. W., Wright, J. S., Sneden, C., Laird, J. B., Aguilar, L. A. & Latham, D. W. 1997, AJ 114, 363
Domínguez, Höflich, & Straniero]dhs01 Domínguez, I., Höflich, P. & Straniero, O. 2001, ApJ, 557, 279
Fulbright, J. P. 2002, AJ, 123, 404
Hashimoto, M., Nomoto, K. & Thielemann, F.-K. 1989, A&A, 210, L5
Hashimoto, M., Nomoto, K., Tsujimoto, T. & Thielemann, F.-K. 1996, in IAU Coll. 145, Supernovae and Supernova Remnants, ed. R. McCray & Z. Wang (Cambridge: Cambridge University Press), 157
Hix, W. R. & Thielemann, F.-K. 1996, ApJ, 460, 869
Höflich, P., Gerardy, C. L., Fesen, R. A. & Sakai, S. 2002, ApJ, 568, 791
Höflich, P. & Khokhlov, A. 1996, ApJ, 457, 500
Höflich, Khokhlov, & Wheeler]hkw95 Höflich, P., Khokhlov, A. M. & Wheeler, J. C. 1995, ApJ, 444, 831
Höflich, Wheeler, & Thielemann]hwt98 Höflich, P., Wheeler, J. C. & Thielemann, F. K. 1998, ApJ, 495, 629
Holweger, H. 2001, in AIP Conf. Proc. 598, Solar and Galactic Composition: A Joint SOHO/ACE Workshop, ed. R. F. Wimmer-Schweingruber (New York: AIP), 23
Ivans, I. I., Sneden, C., James, C. R., Preston, G. W., Fulbright, J. P., Höflich, P. A., Carney, B. W., & Wheeler, J. C. 2003, ApJ, 592, 906
Iwamoto, K., Brachwitz, F., Nomoto, K., Kishimoto, N., Umeda, H., Hix, W. R. & Thielemann, F.-K. 1999, ApJS, 125, 439
James, C. R. 1998, BAAS, 20, 1321
James, C. R. 2000, Ph.D. Thesis, University of Texas, Austin
King, J. R. 1997, AJ, 113, 2303
Nissen P. E. & Schuster W. J. 1997, A&A, 326, 751
Nomoto, K. & Hashimoto, M. 1988, Phys. Rep., 163, 13
Nomoto, Thielemann, & Yokoi]nty84 Nomoto, K., Thielemann, F.-K. & Yokoi, K. 1984, ApJ, 286, 644
Pagel, B. E. G. & Tautvaisiene, G. 1995, MNRAS, 276, 505
Preston, G. W. & Sneden, C. 2000, AJ, 120, 1014
Reetz, J. 1999, A&SS, 265, 171
Sneden, C., Cowan, J. J., Lawler, J. E., Ivans, I. I., Burles, S., Beers, T. C. Primas, F., Hill, V., Truran, J. W., Fuller, G. M., Pfeiffer, B., & Kratz, K.-L. 2003, ApJ, 591, 936
Stephens, A. & Boesgaard, A. M. 2002, AJ, 123, 1647
Thielemann, F.-K., Nomoto, K. & Hashimoto, M. 1996, ApJ, 386, L13
Thielemann, F.-K., Nomoto K. & Yokoi, K. 1986, A&A, 158, 17
Timmes, Woosley, & Weaver]tww95 Timmes, F. X., Woosley, S. E., & Weaver, T. A. 1995, ApJS, 617
Tinsley, B. M. 1979, ApJ, 229, 1046
Tsujimoto, T., Nomoto, K., Yoshii, Y., Hashimoto, M., Yanagida, S. & Thielemann, F.-K. 1995, MNRAS, 277, 945
Umeda, H. & Nomoto, K. 2002, ApJ, 565, 385
van den Bergh, S. & Tammann, G. A. 1991, ARA&A, 29, 363
Woosley, S. E., Langer, N. & Weaver, T. A. 1995, ApJ, 448, 315