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Chemical Abundances in the Universe: Connecting First Stars to Planets
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The first Galactic stars and chemical enrichment in the halo

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Abstract. The cosmic microwave background and the cosmic expansion can be interpreted as evidence that the Universe underwent an extremely hot and dense phase about 14 Gyr ago. The nucleosynthesis computations tell us that the Universe emerged from this state with a very simple chemical composition: H, ^{2}H, ^{3}He, ^{4}He, and traces of ^{7}Li. All other nuclei where synthesised at later times. Our stellar evolution models tell us that, if a low-mass star with this composition had been created (a "zero-metal" star) at that time, it would still be shining on the Main Sequence today. Over the last 40 years there have been many efforts to detect such primordial stars but none has so-far been found. The lowest metallicity stars known have a metal content, Z, which is of the order of $10^{-4}Z_{\odot}$. These are also the lowest metallicity objects known in the Universe. This seems to support the theories of star formation which predict that only high mass stars could form with a primordial composition and require a minimum metallicity to allow the formation of low-mass stars. Yet, since absence of evidence is not evidence of absence, we cannot exclude the existence of such low-mass zero-metal stars, at present. If we have not found the first Galactic stars, as a by product of our searches we have found their direct descendants, stars of extremely low metallicity ($Z \leqslant 10^{-3}Z_{\odot}$). The chemical composition of such stars contains indirect information on the nature of the stars responsible for the nucleosynthesis of the metals. Such a fossil record allows us a glimpse of the Galaxy at a look-back time equivalent to redshift $z = 10$, or larger. The last ten years have been full of exciting discoveries in this field, which I will try to review in this contribution.

Keywords. hydrodynamics, line: formation, nucleosynthesis, stars: abundances, stars: Population II, Galaxy: abundances, Galaxy: evolution, Galaxy: halo

1. Introduction

The quest for the First Stars and their immediate descendants has been a field of very active research, both in the high redshift and in the local Universe. In this review I will only deal with advances in the local Universe, mainly focusing on literature which appeared in the last four years. I refer the reader to the reviews of Beers & Christlieb (2005) and Bonifacio (2007) for the earlier literature. I also largely omit the results on neutron-capture elements, since this is covered by another review in this Symposium (Sneden et al. 2009) and I refer to the review Sneden et al.(2008) for older literature. I will touch only briefly on the topic of Carbon Enhanced Metal Poor stars, which is covered by the review of Aoki (2009) in this Symposium. Finally I will largely ignore the abundant literature on lithium, which should be discussed in this volume by the contributions of Mélendez et al. (2009), Sbordone et al. (2009) and Steffen et al. (2009). I will try to concentrate on the observations, without trying to review their theoretical interpretation.

2. The lowest metallicity stars

In the search of a "zero metal" star, many Extremely Metal Poor (EMP) stars have been discovered thanks to the exploitation of the objective-prism surveys HK (Beers et al. 1985, Beers et al. 1992, Beers 1999), Hamburg-ESO (Christlieb 2003,Christlieb et al. 2008) and, more recently the Sloan Digital Sky Survey (York et al. 2000). Both from the observational and from the theoretical point of view it is important to establish if there is a threshold in metallicity, below which no low-mass stars exist. For this reason we would like to know what is the lowest metallicity found among stars. There are different answers, depending on how you define metallicity. The element whose abundance is most easily measured is iron, so that many people define metallicity as the iron abundance, or in spectroscopic notation, [Fe/H]†. The scientific community became extremely excited by the discovery of the Hyper Metal Poor stars (HMP, according to the nomenclature proposed by Beers & Christlieb 2005), with [Fe/H] of the order of –5, or lower. The class contains up to now only three stars, all extracted from the Hamburg-ESO Survey: HE 0107-5240 ([Fe/H]=–5.3, Christlieb et al. 2002) HE 1327-2326 ([Fe/H]=–5.4, Frebel et al. 2005) and HE 0557-4840 ([Fe/H]=–4.8, Norris et al. 2007). A single element would be a fair tracer of the global metallicity if the element-to-element abundance ratios were Universal, but they are not. The three above stars are characterised by a large over-abundance of C, N and O (see Collet et al. 2006 for an analysis of HE 0107-5240 and HE 1327-2326, based on hydrodynamical models). This peculiar chemical composition implies that their metallicity Z, the mass fraction of elements heavier than He, is comparable to that of Globular Clusters and Halo stars with [Fe/H]~ -2.0, for this reason I think that the nomenclature proposed by Beers & Christlieb (2005) is somewhat misleading and I suggest that Hyper Fe Poor stars (HFeP) would be preferable‡. Beyond the purely semantic issue there is obviously the more fundamental question of the age of these and other EMP stars. In a naive approach to chemical evolution one expects a well defined age-metallicity relation and, if so, is a star of very low Fe, more "pristine" than a star of very low Z ? The evidence, both in our and external galaxies is that in fact chemical evolution can be very complex and a simple age-metallicity relation may not exist. In my view there is no compelling evidence that the HFeP stars are more pristine than other EMP stars and, in fact, all possibilities are open: they could be older, coeval or younger and they may, indeed, show a spread in ages. Precise distances from the GAIA mission (Perryman et al. 2001) will certainly shed new light on this issue. I would also like to mention the intriguing evidence shown by Venn & Lambert(2008), that the abundance pattern in the HFeP stars is similar to what observed in dust-forming stars, such as post-AGB stars. Whether the HFeP stars are indeed dusty objects or not can be tested directly by measuring the abundance of the volatile element S, and efforts are in progress in this direction.

If we now turn our attention to the extremely low Z stars, the situation is clear, the record holder is CD $-38°245$ discovered by Bessell & Norris(1984), with [Fe/H]=–4.2 (Cayrel et al. 2004), no measurement of C, N or O, but strong enhancements can be excluded, thus a value of Z which is of the order of 10^{-4} the solar value. There is a handful of giant and sub-giant stars which have a comparable metallicity: BS 16467-062, CS 22172-002, CS 22885-096 (Cayrel et al. 2004), BS 16076-006 (Bonifacio et al. 2007), CS 30336-049 (Lai et al. 2008) and HE 1424-0241 (Cohen et al. 2007). The latter star has a markedly different chemical composition with respect to the others, showing a very

† $[X/Y] = \log(X/Y)-\log(X/Y)_{\odot}$
‡ Hyper Iron Poor (HIP) could be confused with Hipparcos numbers.

low silicon abundance (1/10 of the iron), but a "normal" Mg abundance. Should oxygen be under-abundant like Si, this would be the most metal-poor object known.

3. High resolution surveys

Several groups have began an homogeneous chemical analysis of large numbers of EMP stars, based on data collected with 8m class telescopes. In this context "large" means of the order of a few tens. The "First Stars" group, led by R. Cayrel has published detailed abundances for giant (Cayrel et al. 2004) and dwarf (Bonifacio et al. 2009a) stars based on spectra collected with UVES at the VLT. The "0Z project", led by J. Cohen, relied on spectra obtained with HIRES at Keck (Cohen et al. 2004, Cohen et al. 2008). Final the group led by D. Lai has made use of both ESI (Lai et al. 2004) and HIRES (Lai et al. 2008) at Keck. The good news is that the results of these three groups agree very well, for the stars in common. The comparison of the measured equivalent widths is always very good, in spite of the differences in observational data and technique for measurement. The abundances can differ by up to a factor of two, however the differences are well understood in terms of different atmospheric parameters (obtained with different methods), different model atmospheres employed, different lines selected. All three groups have published full details of their analysis, thus making it possible (and perhaps desirable) a homogeneous analysis of all the available data. It should be however pointed out that, even without such an homogenisation, the picture provided by the abundance ratios measured by each group is highly consistent.

A special place is held by the HERES survey (Christlieb et al. 2004, Barklem et al. 2005). By means of a "snapshot" strategy, limited spectral coverage and medium S/N ratios, it provided detailed abundances for hundreds of stars. The chemical information is not as complete or as accurate as that afforded by the high S/N studies, but the large numbers involved are indeed highly valuable. The general picture emerging from the abundance ratios of the HERES survey is consistent with that coming from the high S/N studies.

The CASH project (Frebel et al. 2008a) is under way at the Hoberly-Eberly telescope and has so far published the first paper of the series (Roederer et al. 2008), but see also Roederer et al. (2009) in this volume. It is expected to produce highly interesting results in the next few years.

In the course of these surveys of EMP stars it is only natural to note some extreme objects, whose chemical composition departs from that of the vast majority of others, at the same metallicity. For most of these objects we do not have a clear idea of the cause for these peculiar chemical composition. I already mentioned HE 1424-0241 and its extraordinarily low Si abundance. Perhaps related to this is SDSS J234723.64+010833.4 (Lai et al. 2009) underhanced in Mg ([Mg/Fe]=–0.1) and overenhanced in Ca ([Ca/Fe]=+1.1) At the opposite side there is BS 16934-002 (Aoki et al. 2007), with [Fe/H]=–2.7 and an extreme enhancement of α elements ([Mg/Fe]=+1.2, [O/Fe]=+1.1) The giant HK II 17435-00532 (Roederer et al. 2008), shows an extraordinarily high lithium abundance (A(Li)=2.1) and is enhanced in neutron capture elements. It certainly came as a surprise to me to learn that the subgiant BD+44°493 (V=9.1) has a metallicity as low as [Fe/H]=–3.7 (Ito et al. 2009a). The reason why this star has been for so long overlooked is that it is a CEMP star, thus having a metal-rich appearance at low resolution. Its brightness allowed to attempt the measurement of Be. No Be was detected, as expected from the linear decrease of Be with metallicity. The fact that the star shows a measurable Li abundance (A(Li)=1.04) allows to discard Be destruction in the star itself(Ito et al. 2009b). Finally I would like to mention the possible paradox posed by star CS 30322-023

(Masseron et al. 2006), whose extremely high luminosity (log g $\leqslant -0.3$) qualifies it as a TP-AGB star. The abundance pattern of this star suggests an intermediate mass of $2M_{\odot}$ or larger. However, its distance (about 50 kpc) implies it belongs to the outer Halo, where no recent star formation has occurred.

4. Highlights of research on EMP stars

In a somewhat arbitrary manner I want to mention here some of the results which I think are most exciting. I will start with Be, this element, which is a pure product of cosmic ray spallation shows a linear decrease with metallicity. This has now been confirmed down to the very lowest metallicities, with no hint of a “Be plateau”, by the works of Rich & Boesgaard(2009) and Tan et al.(2009). On the other hand the large survey conducted by Smiljanic et al. (2009a) allowed to definitely establish the value of Be as a chronometer (see also Smiljanic et al. 2009b in this volume).

For the understanding of the Galactic chemical evolution the knowledge of isotopic ratios, besides that of abundances, provides important insight. The isotopic ratios of Li are covered in this volume by Steffen et al. (2009) and those on neutron capture elements by Sneden et al. (2009). I would like here to cite the important progress which has been made on the measurement of Mg isotopic ratios (Yong et al. 2003, Yong et al. 2004, Yong et al. 2006, Meléndez & Cohen 2009), which provide direct evidence of the onset of the contribution of AGB stars to the chemical evolution. Such measurements are extremely difficult and further effort in this direction is strongly encouraged.

Binary stars always provide us some constraint on the masses of the components, thus their study is strongly encouraged. They often provide us some puzzles, like the EMP system CS 22876-32 ([Fe/H]=–3.6) for which González Hernández et al. (2008) have been able to determine the Li abundance in both components and, surprisingly, the abundance differs by 0.4 dex, although the effective temperature of both components is too high to expect lithium to be depleted by convection. Another puzzle comes from the system CS 22964-161 (Thompson et al. 2008) in which both components show a high enhancement in carbon and s-process elements, as expected if mass-transfer from an AGB companion had occurred. The puzzle is that the system is double lined and both stars appear to be on the Main Sequence. This points to the fact that this was once a triple system and the most massive star, after its AGB phase, has in fact been lost. In this context it is interesting to note that a quadruple metal-poor system has recently been discovered. Rastegaev (2009) has shown that G89-14 ([Fe/H]=–1.9) is indeed a highly hierarchical quadruple system. So perhaps the existence of a triple system is not so uncommon. There is a further anomaly of CS 22964-161, its lithium abundance is A(Li)=2.2, while we would expect a low value, after the transfer from an AGB companion, which enhanced the C abundance. However, this is a feature which is shared by other CEMP stars, for example SDSSJ1036+1212 (Behara et al. 2009b in this volume).

Another extremely exciting finding is that we are now beginning to find the EMP stars in Local Group galaxies. The first one found was Draco 119 (Shetrone et al. 2001), and the second was found in the Sgr dSph (Bonifacio et al. 2006), however for some time these were considered the exceptions. Especially after the DART collaboration announced a clear lack of EMP stars in the LG (Helmi et al. 2006) it was widely felt that these stars were a peculiarity of the Milky Way. The situation has now largely changed, in the first place the DART collaboration revised the metal-poor end of their calibration of the Ca II IR triplet (see Hill 2009, these proceedings), in the second place a number of new EMP stars has been discovered in LG galaxies. Cohen & Huang(2009) discovered a second EMP star in Draco, Frebel et al.(2009) discovered two EMP stars in UMa II and one in

Coma Berenices, Norris et al.(2008) discovered eight stars with [Fe/H]~ -3 in Bootes I and one with [Fe/H]~ -3.5. On the other hand Sextans does not show any stars below [Fe/H]$= -3$, although Aoki et al.(2009) found six below –2.5. The conclusion is that EMP stars are to be found everywhere and their detailed abundances will tell us something on the first stars in their host galaxies.

5. Deviations from LTE

The bulk of the chemical abundances published to date assume Local Thermodynamic Equilibrium (LTE) in the line formation computations. We know that this is an idealised assumption and there is a very active research on relaxing it.

The odd elements Na and Al show sizeable NLTE effects and all abundances based on LTE analysis should be discarded (Gehren et al. 2006, Andrievsky et al. 2007, Andrievsky et al. 2008). Magnesium shows a dwarf/giant discrepancy and should also be treated in NLTE (Gehren et al. 2006, Spite et al. 2009). The trend of [Mg/Fe] with metallicity is flat in both cases, but higher in NLTE (~ 0.6 dex) than in LTE. In fact when Mg is compute in NLTE [O/Mg]~ 0 at all metallicities (Spite et al. 2009). Silicon is also one of the elements which shows a disturbing dwarf/giant discrepancy (Bonifacio et al. 2009a) and the computations of Shi et al.(2009) suggest that NLTE is indeed important for Si in metal-poor stars. A thorough NLTE analysis of Si in EMP stars is strongly encouraged.

Carbon is also an element which shows a dwarf/giant discrepancy (Bonifacio et al. 2009a), although in this case the discrepancy might have an astrophysical cause (modification of the abundances of giant stars due to mixing) it is more likely that it is due to an inadequacy in the analysis. C abundances in metal-poor stars rely mainly on the G-band and up to now NLTE analysis of CH lines have not been published. Such an investigation, however is strongly encouraged.

Some abundance ratios have been discovered early on, to depart significantly from the solar value in metal-poor stars. For example McWilliam et al.(1995) found that the [Cr/Fe] and [Mn/Fe] ratios become increasingly lower for the most metal-poor stars, while the [Co/Fe] ratios increase. These findings were consistently confirmed with lower and lower scatter, by all subsequent investigations and were generally interpreted as features of the Galactic chemical evolution (see e.g. Prantzos 2008 and references therein). However it now appears very likely that the trend of Cr is spurious and due to the neglect of NLTE effects. As pointed out by Lai et al.(2008) and Bonifacio et al.(2009a), there is a discrepancy between dwarfs and giants, and if only Cr II lines are used (possible only for giants) [Cr/Fe] appears to be consistently solar at all metallicities. Theoretical computations by Bergemann & Gehren (2009) confirm that a NLTE analysis implies a solar [Cr/Fe]. A similar dwarf/giant discrepancy is present also for Mn (Bonifacio et al. 2009a) and the NLTE computations of Bergemann & Gehren(2008) indeed confirm that the trend is spurious. Also the [Co/Fe] ratio displays a dwarf/giant discrepancy (Bonifacio et al. 2009a), however in this case, the NLTE analysis of Bergemann et al.(2009) implies and even steeper increase of this ratio with decreasing metallicities. The NLTE trend for [Cr/Fe] (flat at solar metallicity) certainly goes in the direction to satisfy chemical evolution models, and associated stellar yields. On the contrary the NLTE trends of Mn and Co cannot be explained by current models.

The situation for copper is unclear. At very low metallicity the copper abundances must rely on the strong resonance lines of Mult. 1 and the discrepancy of the abundances derived from these lines and those derived from those of Mult. 2 cast serious doubts on the validity of LTE for either multiplet (Bonifacio et al. 2009b).

For zinc the situation is puzzling. Bonifacio et al.(2009a) found a disturbing dwarf/giant

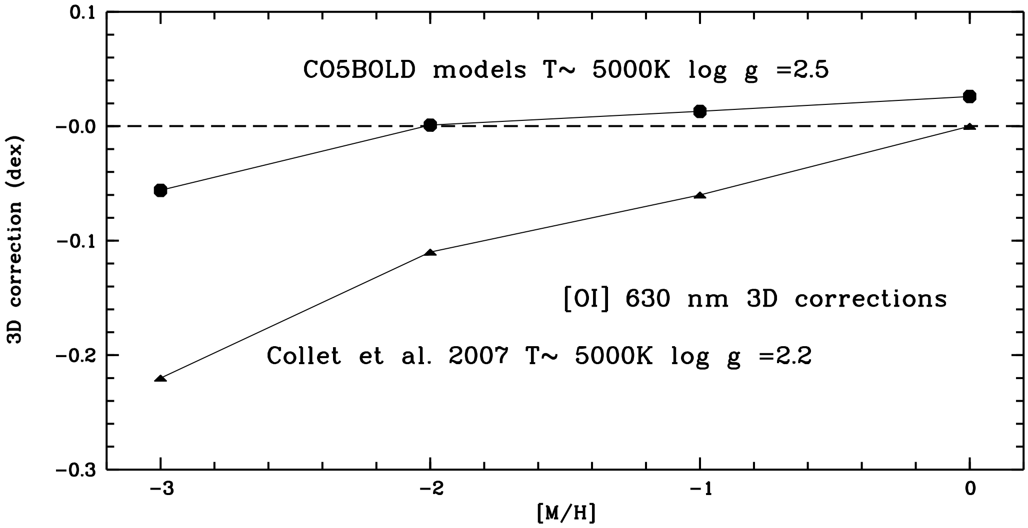

Figure 1. 3D corrections for the [OI] 630 nm line, for giant stars computed from $\mathrm{CO^5BOLD}$ models, compared with those computed by Collet et al. (2007), from models computed with the Stein& Nordlund code (Stein & Nordlund 1998). The difference is non-negligible, and it is likely rooted in the different microphysics of the two codes, but also in the different models used as 1D reference to compute the 3D corrections.

discrepancy, however the NLTE computations of Takeda et al.(2005) imply small NLTE corrections for Zn and in any case not significantly different for giants and dwarfs. Also granulation effects are unlikely to be the cause of this discrepancy. In the case of zinc we are also facing the problem of small number statistics, since for very few dwarf stars zinc has been measured. The issue should be further investigated both from the theoretical and observational point of view.

The NLTE effects may be relevant also for neutron capture elements. Up to now results for Ba have been published (Mashonkina et al. 2008, Andrievsky et al. 2009) and in this case the large star-to-star scatter at any metallicity is confirmed by the NLTE analysis, pointing to a poor mixing of these elements in the early Galaxy.

6. Granulation effects

Besides LTE, the most important simplifying assumption made in the analysis of stellar spectra is that of a static atmosphere. Thus the majority of analysis rely on 1D hydrostatic model atmospheres. In the last 10 years a considerable advance has come through the use of three dimensional hydrodynamical simulations of stellar atmospheres (3D models for short). All the analysis published so far rely on simulations computed either with the code of Stein & Nordlund(1998) or with the $\mathrm{CO^5BOLD}$ code (Freytag et al. 2002, Freytag et al. 2003, Wedemeyer et al. 2004). Such models are more physically motivated than 1D models, although there is still considerable work to validate them and bring them at the level of maturity of current 1D models. The treatment of opacity in such models is based on an opacity binning scheme (Nordlund 1982, Ludwig 1992, Ludwig, Jordan, & Steffen 1994), however the optimal number of bins to employ and their definition is still a matter of investigation. Behara et al.(2009a) found significant differences in the temperature structure of the outer layers for models computed using six or twelve opacity bins.

To illustrate some of the problems I computed the "3D correction", as defined by Caffau & Ludwig(2007), for for the [OI] 630 nm line, from four models of giant star extracted from the CIFIST grid of 3D models (Ludwig et al. 2009). In Fig. 1 I compare these corrections with those published by Collet et al. (2007). The difference is small, but non-negligible in the context of Galactic chemical evolution. My computations suggest that the 1D-based oxygen abundances of Cayrel et al.(2004) require no correction for granulation effects, while the computations of Collet et al. (2007) imply a downward revision by 0.2 dex or perhaps larger. At the time of writing I am unable to say which of the two computations is right (if any !). I can however point out two differences which are likely to be relevant: *i)* the models of the CIFIST grid are computed using six opacity bins, while those of Collet et al. (2007) use four opacity bins; *ii)* my corrections are computed using as reference 1D model an LHD model (see e.g. Caffau et al. 2008), which employs the same microphysics of CO^{5}BOLD, while Collet et al. (2007) use a MARCS model (Gustafsson et al. 2008, and references therein). The role of these differences still needs to be explored.

It should be clear that the choice of using to hydrodynamical models forces us to make some simplifications which are not done in 1D hydrostatic models. The most obvious one is the role of scattering. While this is properly treated in existing 1D model atmosphere and line formation codes, it is treated as true absorption in all 3D codes. It remains to be investigated if this approximation is acceptable or not.

In the meanwhile it is exciting to note a strong effort in a systematic application of 3D models to abundance analysis (Collet et al. 2006, Collet et al. 2007, Cayrel et al. 2007, González Hernández et al. 2008, Frebel et al. 2008b, Collet et al. 2009, Bonifacio et al. 2009a , González Hernández et al. 2009)

All the aspects of spectroscopic analysis need to be explored and revised in the light of hydrodynamical models. One noticeable example are the Balmer lines and their role in temperature diagnostic (Ludwig et al. 2009). One of the things that we still lack from 3D models are extensive grids of theoretical fluxes and colours, although efforts in this direction are underway (Kučinskas et al. 2009,Casagrande 2009)

The future looks very bright and busy, for the vast number of tasks to be accomplished. I hope the community will continue with the enthusiasm shown in the last decade.

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References

Andrievsky, S. M., Spite, M., Korotin, S. A., Spite, F., Bonifacio, P., Cayrel, R., Hill, V., & François, P. 2007, *A&A*, 464, 1081

Andrievsky, S. M., Spite, M., Korotin, S. A., Spite, F., Bonifacio, P., Cayrel, R., Hill, V., & François, P. 2008, *A&A*, 481, 481

Andrievsky, S. M., Spite, M., Korotin, S. A., Spite, F., François, P., Bonifacio, P., Cayrel, R., & Hill, V. 2009, *A&A*, 494, 1083

Aoki, W. 2009 *IAU Symp.* 265, p. 111

Aoki, W., et al. 2007, *ApJ*, 660, 747

Aoki, W., et al. 2009, *A&A*, 502, 569

Barklem, P. S., et al. 2005, *A&A*, 439, 129
Beers, T. C. 1999, *Ap&SS*, 265, 547
Beers, T. C., & Christlieb, N. 2005, *ARAA*, 43, 531
Beers, T. C., Preston, G. W., & Shectman, S. A. 1985, *AJ*, 90, 2089
Beers, T. C., Preston, G. W., & Shectman, S. A. 1992, *AJ*, 103, 1987
Behara, N. T., Ludwig, H. -G., Bonifacio, P., Sbordone, L., González Hernández, J. I., & Caffau, E. 2009a, *MemSAI*, 80, 732
Behara, N. T., Bonifacio, P., Ludwig, H. -., Sbordone, L., González Hernández, J. I., & Caffau, E. 2009b, *IAU Symp.* 265, p. 122
Bergemann, M., & Gehren, T. 2008, *A&A*, 492, 823
Bergemann, M., & Gehren, T. 2009, *IAU Symp.* 265, p. 348
Bergemann, M., Pickering, J. C., & Gehren, T. 2009, arXiv:0909.2178
Bessell, M. S., & Norris, J. 1984, *ApJ*, 285, 622
Bonifacio, P., et al. 2006, *Chemical Abundances and Mixing in Stars in the Milky Way and its Satellites, ESO ASTROPHYSICS SYMPOSIA*. ISBN 978-3-540-34135-2. Springer-Verlag, 2006, p. 232
Bonifacio, P. 2007, *EAS Publications Series*, 24, 251
Bonifacio, P., et al. 2007, *A&A*, 462, 851
Bonifacio, P., et al. 2009a, *A&A*, 501, 519
Bonifacio, P., Caffau, E., & Ludwig, H. -. 2009b, *MemSAI*80, 736
Caffau, E., & Ludwig, H.-G. 2007, *A&A*, 467, L11
Caffau, E., Ludwig, H.-G., Steffen, M., Ayres, T. R., Bonifacio, P., Cayrel, R., Freytag, B., & Plez, B. 2008, *A&A*, 488, 1031
Casagrande, L. 2009, *MemSAI*, 80, 724
Cayrel, R., et al. 2004, *A&A*, 416, 1117
Cayrel, R., et al. 2007, *A&A*, 473, L37
Christlieb, N. 2003, *Reviews in Modern Astronomy*, 16, 191
Christlieb, N., et al. 2002, *Nature*, 419, 904
Christlieb, N., et al. 2004, *A&A*, 428, 1027
Christlieb, N., Schörck, T., Frebel, A., Beers, T. C., Wisotzki, L., & Reimers, D. 2008, *A&A*, 484, 721
Cohen, J. G., & Huang, W. 2009, *ApJ*, 701, 1053
Cohen, J. G., et al. 2004, *ApJ*, 612, 1107
Cohen, J. G., McWilliam, A., Christlieb, N., Shectman, S., Thompson, I., Melendez, J., Wisotzki, L., & Reimers, D. 2007, *ApJ*, 659, L161
Cohen, J. G., Christlieb, N., McWilliam, A., Shectman, S., Thompson, I., Melendez, J., Wisotzki, L., & Reimers, D. 2008, *ApJ*, 672, 320
Collet, R., Asplund, M., & Trampedach, R. 2006, *ApJ*, 644, L121
Collet, R., Asplund, M., & Trampedach, R. 2007, *A&A*, 469, 687
Collet, R., Nordlund, Å., Asplund, M., Hayek, W., & Trampedach, R. 2009, *MemSAI*, 80, 716
Frebel, A., et al. 2005, *Nature*, 434, 871
Frebel, A., Allende Prieto, C., Roederer, I. U., Shetrone, M., Rhee, J., Sneden, C., Beers, T. C., & Cowan, J. J. 2008a, *New Horizons in Astronomy, ASPC*, 393, 203
Frebel, A., Collet, R., Eriksson, K., Christlieb, N., & Aoki, W. 2008b, *ApJ*, 684, 588
Frebel, A., Simon, J. D., Geha, M., & Willman, B. 2009, arXiv:0902.2395
Freytag, B., Steffen, M., & Dorch, B. 2002, *Astronomische Nachrichten*, 323, 213
Freytag, B., Steffen, M., Wedemeyer-Böhm, S., & Ludwig, H.-G. 2003, *CO5BOLD User Manual*, http://www.astro.uu.se/ bf/co5bold_main.html
Gehren, T., Shi, J. R., Zhang, H. W., Zhao, G., & Korn, A. J. 2006, *A&A*, 451, 1065
González Hernández, J. I., et al. 2008, *A&A*, 480, 233
González Hernández, J. I., et al. 2009, *A&A*, 505, L13
Gustafsson, B., Edvardsson, B., Eriksson, K., Jørgensen, U. G., Nordlund, Å., & Plez, B. 2008, *A&A*, 486, 951
Helmi, A., et al. 2006, *ApJ*, 651, L121
Hill, V. 2009, *IAU Symp.* 265, p. 219

Ito, H., Aoki, W., Honda, S., & Beers, T. C. 2009a, *ApJ*, 698, L37

Ito, H., Aoki, W., Honda, S., Beers, T. C., & Tominaga, N. 2009b, *IAU Symp.* 265, p. 124

Kučinskas, A., Ludwig, H. -G., Caffau, E., & Steffen, M. 2009, *MemSAI*, 80, 720

Lai, D. K., Bolte, M., Johnson, J. A., & Lucatello, S. 2004, *AJ*, 128, 2402

Lai, D. K., Bolte, M., Johnson, J. A., Lucatello, S., Heger, A., & Woosley, S. E. 2008, *ApJ*, 681, 1524

Lai, D. K., Rockosi, C. M., Bolte, M., Johnson, J. A., Beers, T. C., Lee, Y. S., Allende Prieto, C., & Yanny, B. 2009, *ApJ*, 697, L63

Ludwig, H.-G. 1992, PhDT, University of Kiel

Ludwig, H.-G., Jordan, S., & Steffen M. 1994, *A&A*, 284, 105

Ludwig, H. -., Caffau, E., Steffen, M., Freytag, B., Bonifacio, P., & Kučinskas, A. 2009, *MemSAI*, 80, 708

Ludwig, H.-G., Behara, N. T., Steffen, M., & Bonifacio, P. 2009, *A&A*, 502, L1

Mashonkina, L., et al. 2008, *A&A*, 478, 529

Masseron, T., et al. 2006, *A&A*, 455, 1059

McWilliam, A., Preston, G. W., Sneden, C., & Searle, L. 1995, *AJ*, 109, 2757

Meléndez, J., & Cohen, J. G. 2009, *ApJ*, 699, 2017

Mélendez, J., Casagrande, L., Ramirez, I. 2009 *IAU Symp.* 265, p. 71

Nordlund, Å. 1982, *A&A*, 107, 1

Norris, J. E., Christlieb, N., Korn, A. J., Eriksson, K., Bessell, M. S., Beers, T. C., Wisotzki, L., & Reimers, D. 2007, *ApJ*, 670, 774

Norris, J. E., Gilmore, G., Wyse, R. F. G., Wilkinson, M. I., Belokurov, V., Evans, N. W., & Zucker, D. B. 2008, *ApJ*, 689, L113

Perryman, M. A. C., et al. 2001, *A&A*, 369, 339

Prantzos, N. 2008, *EAS Publications Series*, 32, 311

Rastegaev, D. A. 2009, *Astronomy Letters*, 35, 466

Rich, J. A., & Boesgaard, A. M. 2009, *ApJ*, 701, 1519

Roederer, I. U., et al. 2008, *ApJ*, 679, 1549

Roederer, I. U. 2009 *IAU Symp.* 265, p. 368

Sbordone, L., Bonifacio, P., Caffau, E., et al. 2009 *IAU Symp.* 265, p. 75

Shetrone, M. D., Côté, P., & Sargent, W. L. W. 2001, *ApJ*, 548, 592

Shi, J. R., Gehren, T., Mashonkina, L., & Zhao, G. 2009, *A&A*, 503, 533

Smiljanic, R., Pasquini, L., Bonifacio, P., Galli, D., Gratton, R. G., Randich, S., & Wolff, B. 2009a, *A&A*, 499, 103

Smiljanic, R., Pasquini, L., Bonifacio, P., Galli, D., Barbuy, B., Gratton, R., & Randich, S. 2009b, *IAU Symp.* 265, p. 134

Sneden, C., Cowan, J.J. & Gallino, R. 2009 *IAU Symp.* 265, p. 46

Sneden, C., Cowan, J. J., & Gallino, R. 2008, *ARAA*, 46, 241

Spite, M., Spite, F., Bonifacio, P., Andrievsky, S., Cayrel R., François, P., Korotin, S. 2009 *IAU Symp.* 265, p. 380

Steffen, M., Cayrel, R., Bonifacio, P., Ludwig, H.-G., Caffau, E. 2009 *IAU Symp. 265*, p. 23

Stein, R. F., & Nordlund, A. 1998, *ApJ*, 499, 914

Takeda, Y., Hashimoto, O., Taguchi, H., Yoshioka, K., Takada-Hidai, M., Saito, Y., & Honda, S. 2005, *PASJ*, 57, 751

Tan, K. F., Shi, J. R., & Zhao, G. 2009, *MNRAS*, 392, 205

Thompson, I. B., et al. 2008, *ApJ*, 677, 556

Venn, K. A., & Lambert, D. L. 2008, *ApJ*, 677, 572

Wedemeyer, S., Freytag, B., Steffen, M., Ludwig, H.-G., & Holweger, H. 2004, *A&A*, 414, 1121

Yong, D., Lambert, D. L., & Ivans, I. I. 2003, *ApJ*, 599, 1357

Yong, D., Lambert, D. L., Allende Prieto, C., & Paulson, D. B. 2004, *ApJ*, 603, 697

Yong, D., Aoki, W., & Lambert, D. L. 2006, *ApJ*, 638, 1018

York, D. G., et al. 2000, *AJ*, 120, 1579