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CS 29497-030: Evidence for s-process operation in the Early Galaxy *,**

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Abstract. In the course of the ESO Large Programme "First Stars" (P.I. R. Cayrel), we have observed several stars which were classified as Turn Off (TO) on the basis of the medium resolution survey spectra and colours and yet showed a prominent G band, suggesting a strong C enhancement. Among these CS 29497-030 proved to be an exceptional object: it is very metal poor ([Fe/H]=–2.8), hotter than the Halo Turn Off (T_{eff} = 6650K, log$g$ = 3.5) and C, N and O are all strongly enhanced ([C/Fe] = +2.38, [N/Fe]= +1.88, [O/Fe]= +1.67), as well as Na ([Na/Fe]=+0.52) and all of the $n-$ capture elements. Most striking is the large Pb overabundance ([Pb/Fe]= +3.5). This large Pb overabundance and the overall abundance pattern of $n-$ capture elements may be understood as a signature of the $s-$ process in very low metallicity stars. This strongly suggests that the $s-$ process was fully operative at early times in the Galaxy.

Key words. Nucleosynthesis – Stars: abundances – Stars: binary: spectroscopic – Stars: CS29497-030 – Galaxy: Halo – Galaxy: abundances

1. Introduction

The elements heavier than the iron peak are synthesized mainly through neutron-capture, although in two different modes: slow neutron capture (or $s-$process) in which a β decay always follows a neutron capture and rapid neutron capture (or $r-$ process) in presence of higher neutron fluxes several neutron captures can occur before a β decay takes place. Most isotopes can be formed by either process however the elemental ratios produced by the two processes are markedly different. The site of the $s-$ process is generally accepted to be the intershell region of an Asymptotic Giant Branch (AGB) star. The site of the $r-$ process is uncertain yet it is quite likely linked to core collapse supernovae.

In a pioneering paper aimed at the study of the build up of neutron capture elemnts in the Galaxy Spite & Spite (1978) found both Ba and Y to be over deficient with respect to iron. Moreover the increase of barium seemed to follow that of iron and Spite & Spite suggested a common origin for both in massive, short-lived stars.

* Based on observations made with the ESO Very Large Telescope at Paranal Observatory, Chile (program ID 165.N-0276(A)).

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Table 1. Table 1. Elemental abundances for CS 29497-030

Species	[X/H]	[X/Fe]	σ	n
Li I	<0.00	<2.7	...	...
C I	−0.01	2.69	0.24	22
CH	−0.32	2.38	...	...
CN	−0.82	1.88	...	...
O I	−1.03	1.67	0.1	3
NaI	−2.18	0.52	0.15	2
MgI	−2.16	0.54	0.21	4
MgII	−2.06	0.64	...	1
Al I	−3.37	−0.67	...	1
Si I	−2.75	−0.05	...	1
Si II	−2.10	0.60	...	2
S I	−2.30	0.40	...	1
K I	<-2.00	<0.7	...	...
Ca I	−2.37	0.33	0.17	9
Sc II	−2.40	0.30	0.05	3
Ti I	−2.54	0.16	...	1
Ti II	−2.41	0.29	0.28	19
Cr I	−2.87	−0.17	0.12	6
Cr II	−2.75	−0.05	0.07	4
Mn I	−2.89	−0.19	0.28	3
Mn II	−2.87	−0.17	0.00	2
Fe I	−2.77	−0.07	0.14	55
Fe II	−2.70	−0.00	0.10	5
Co I	−2.28	0.42	0.10	2
Ni I	−2.91	−0.21	0.22	11
Zn I	<-2.80	<-0.10	...	...
Sr II	−1.86	0.84	0.05	2
Y II	−2.14	0.56	0.10	3
Zr II	−1.27	1.43	0.15	3
Ba II	−0.53	2.17	0.25	6
La II	−0.60	2.10	0.10	11
Ce II	−0.98	1.72	0.10	4
Nd II	−0.85	1.85	0.10	8
Eu II	−1.26	1.44	0.15	6
Pb I	0.85	3.55	...	1
$^{12}C/^{13}C$			>10	

Following up on this suggestion Truran (1981) made the hypothesis that in the early Galaxy neutron capture elements are formed only through the $r-$process. The theoretical arguments behind these ideas were essentially:

1. the time necessary for a star to evolve to the AGB, produce the $s-$process elements and return them to the intestellar medium are sufficient for several massive stars to have already evolved and exploded as core collapse SNe raising the mean metallicity of the gas. Thus below some given metallicity threshold there was not enough time for the $s-$process to operate;
2. stellar evolutionary models of the eighties predicted that a zero-metal star should not undergo thermal pulses (Fujimoto et al. 1984), thus at zero or very low metallicity the main site of the $s-$process would not be available.

The second of these arguments has fallen since Chieffi et al. (2001) have shown that thermal pulses occur even in zero-metal stars. The operation of the $s-$ process also requires the presence of seed nuclei and of a suitable neutron source. Goriely & Siess (2001) have shown that, provided there is a partial mixing of protons in the He shell, both conditions can be satisfied and captures may start from ^{12}C. The $s-$process at low metallicity is characterized by a large neutron-to-seed-nucleus ratio and this results in the fact that neutron rich nuclei, in particular Pb, are overproduced with respect to what happens at higher metallicities.

Observationally there is a growing evidence that at least in some cases the $s-$ process is fully operating even at very low metallicities. Lead of s-process origin was detected by Aoki et al. (2000) in the metal-poor star LP 625-44 and Van Eck et al. (2001) found three metal-poor stars in which Pb was over-abundant with respect to nearby neutron-peak elements (Ba, La,Ce) quite likely a signature of the operation of the $s-$process at low metallicity.

In this paper we report the discovery in the very metal poor star CS 29497-030 of a record overabundance of lead ([Pb/Fe]=+3.5) as well as of other n-capture elements. The abundance pattern is indicative of the $s-$ process thus showing that the $s-$process may be fully operating even at very low metallicities.

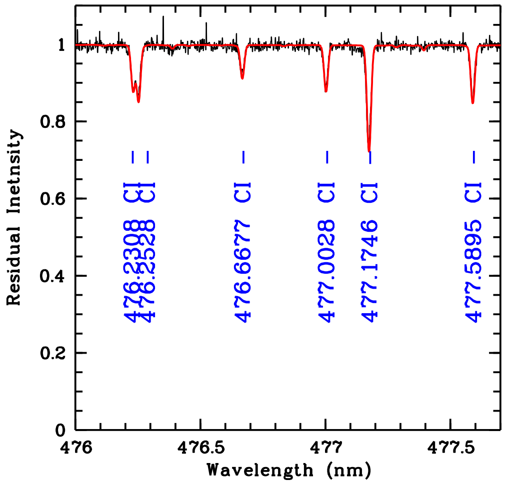

Fig. 1. Examples of the high-excitation CI lines observed in CS 29497-030. The red line is the synthetic spectrum computed with the fitted C abundance, which is 0.3 dex higher than what is derived from the CH lines.

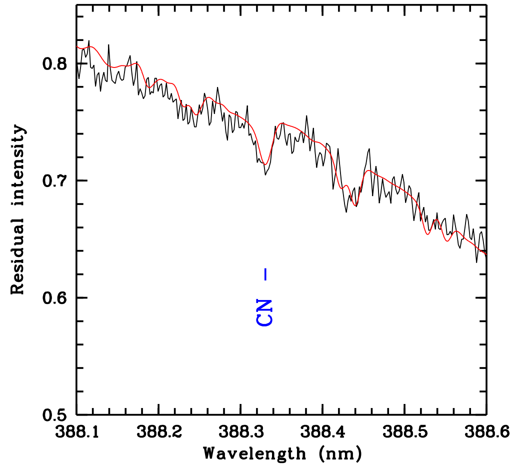

Fig. 2. The CN 388nm bandhead. The black line is the observed spectrum, while the red line is the synthetic spectrum.

2. Observations and data reduction

The spectra were obtained at the VLT-Kuyen 8.2m telescope, using the UVES spectrograph (Dekker et al 2000) at a resolving power of $R = 43000$. The UVES context within MIDAS was used to reduce the spectra. Equivalent-width measurements were performed by fitting gaussian profiles, using the genetic algorithm code described in François et al. (2003).

3. Analysis and results

The analysis was performed using OSMARCS model atmospheres and the TURBOSPECTRUM spectrum synthesis code (by B. Plez). From the Fe I excitation equilibrium we derive $T_{eff} =$ 6650 K, the Fe I/Fe II ionization equilibrium implies log g = 3.5 . From 29 unblende Fe I lines we derive a very low metallicity ([Fe/H]$\simeq$ −2.8), as expected from the low resolution spectra. Carbon appears higly enhanced, both from the CH lines and from the high excitation CI lines shown in Fig. 1. However the latter provide an abundance which is 0.1–0.3 dex higher than that derived from the CH lines. We suspect that this is due to NLTE effects and consider the abundance derived from the CH lines more reliable. Also N is found higly enhanced ([N/Fe]=+1.88) from the very weak CN 388nm bandhead, shown in Fig. 2.

The oxygen abundance was derived from the OI 777.4 nm triplet shown in Fig. 3. Our high [O/Fe]=+1.67 includes an NLTE correction of −0.09 dex as prescribed by Gratton et al. (1999). Our derived O abundance is excetionally high high when compared to most other metal–poor stars (Depagne et al. 2002).

All the $n-$ capture elements appear to be enhanced and especially Pb, the 405.7 nm line is shown in Fig. 4, which has the record value of [Pb/Fe]=+3.5 . The heavy s-process elements (hs: Ba, Ce, La, Nd) are more overabundant than the lighter s-process elements (ls: Sr, Y, Zr). Pb is strongly overabundant with respect to Ba, La, Ce and Nd, for example [Pb/Ba] = +1.38 .

Among iron-peak elements Mn and Cr show a slight underabundance of ~ 0.2 dex

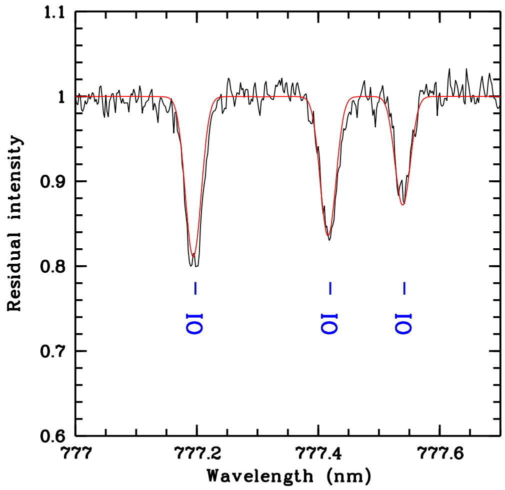

Fig. 3. The OI 777nm triplet. In red the synthetic spectrum

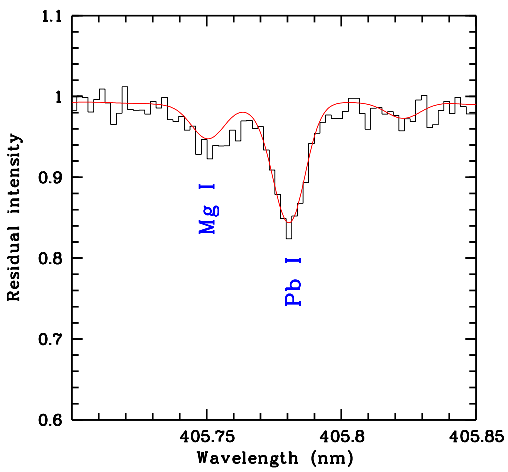

Fig. 4. The Pb I 405.7nm line. The red line is the synthetic spectrum

compared to iron as generally observed in very metal-poor stars.

4. Conclusions

The abundance pattern of the n capture elements seems to point unmistakably to the $s-$process. The large overabundance of Pb with respect to the nearby second-peak $s-$process elements (Ba, La, Ce, Nd) is a signature of the $s-$ process in a low metallicity environment, which is characterized by a large neutron-to-seed ratio. The site of the $s-$process is an Asymptotic Giant Branch companion star which has polluted the surface CS 29497-030 with its nucleosynthesis products, including C, N and, perhaps O. CS 29497-030 is a known binary with a period of 242 days (Sneden et al. 2003) but the companion has not been detected either photometrically or spectroscopically, in agreement with the notion that it is presently a white dwarf.

This star is an extreme case of $s-$ process enriched very metal poor star, 25 such stars are known so far. This shows that the $s-$process was operating at early times in the Galaxy. The importance of its contribution to the general evolution of n capture elements needs still to be assessed, however one can safely state that any realistic model of chemical evolution ought to take into consideration both $r-$ and $s-$ process *at all times*. The hypothesis that all the heavy elements are made only through the $r-$ process at low metallicity (Truran 1981) as an *a priori* should be abandoned.

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