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Letter to the Editor

What can we learn from the r-element distribution of CS 22892-052?

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Abstract. The striking similarity between the solar distribution of r-element abundances in the $56 \le Z \le 76$ range and the corresponding abundance pattern observed in the ultra-metal-poor star CS 22892-052 is analysed. It is found that such an observation does not necessarily imply that the whole $A \gtrsim 70$ distribution of r-nuclides, including Th, suspected to have been engulfed in CS 22892-052 at the same time as the detected elements is solar. Such a conclusion derives from the finding that an *arbitrary* superposition of r-process events that does not fit the whole solar r-process pattern can also account for the CS 22892-052 observations. The interpretation of this result and its implications are discussed.

Key words: nucleosynthesis – nuclear reactions – stars: abundances – solar system: general – stars: CS 22892-052

1. Introduction

The recent observation of r-process elements ranging from Ba to Os, as well as Th, in the ultra-metal-poor halo star CS 22892-052 (Sneden et al., 1996) has brought some renewed excitement in the search of the origin of the heavy elements in the Universe. With a metallicity as low as [Fe/H]=–3.1 and a composition enriched in some pure r-elements, CS 22892-052 provides strong additional evidence that the production of heavy elements by the r-process already took place early in the history of the Galaxy. Moreover, the distribution of some 16 elements between Ba and Os shows a striking similarity with the solar system r-abundance distribution. It is tempting to conclude that this similarity reflects the absence of s-process contribution in this mass range, and that the solar system r-elements must originate from one or only a few astrophysical events, or, equivalently, that any astrophysical event producing r-elements gives rise to a solar system r-abundance distribution. This idea has always been present since Seeger et al. (1965) showed that, within the so-called canonical model, 3 astrophysical events (each of them characterized by one temperature, one neutron density and one irradiation time) are sufficient to explain the gross solar system r-abundance pattern. However, the conclusion that the solar system r-content originates from only a small number of astrophysical events corresponds to an extra step in the interpretation of the data for CS 22892-052. It should also be added that this star presents some puzzling peculiarities in addition to its solar distribution of some r-elements. First, it shows a remarkable overabundance of r-elements with respect to Fe ([Eu/Fe]=+1.7). Second, it is a C-rich star with [C/Fe] = +1 and [O/Fe] $\lesssim$ +0.6. This property is difficult to reconcile with the idea that the r-process develops during the supernova explosion of a massive metal-poor star. The corresponding ejecta is indeed predicted to exhibit a large overabundance of O with respect to C, in contradiction with the CS 22892-052 observations.

The aim of this Letter is to analyse in a critical way if indeed the r-process abundance data made available for CS 22892-052 imply that its *whole* r-process distribution is by necessity essentially solar. The answer to this question is important in order to constrain or unconstrain the nature of the r-process events that have contaminated the Galaxy in the early stages of its history. It is also of interest in order to evaluate the level of reliability of the attempts to build a Th cosmochronometry upon the CS 22892-052 abundance analysis. These attempts indeed rely heavily on the very basic assumption that the Th abundance inherited by that star with respect to the other elements is very close to solar.

2. Prediction of the r-element distribution of CS 22892-052

The close to solar distribution of some 16 r-elements ranging from Ba to Os observed in CS 22892-052 raises quite naturally the question: to what extent can its r-nuclidic abundance distribution be non-solar outside the observed range ? The answer to this question may come from the analysis through r-process

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calculations of the correlation between the production of the Ba to Os elements and the rest of the r-elements.

We first consider a *random* superposition of about 10 equally weighted astrophysical events with paths characterized by S_a^0 values in the $0.9 \lesssim S_a^0[\mathrm{MeV}] \lesssim 3.4$ range[1]. These events are taken at a constant temperature $T_9 = 1.4$ and at constant neutron densities evenly distributed in the $10^{22} \leq N_n[\mathrm{cm}^{-3}] \leq 10^{31}$ range. For each event, a full time-dependent network is used to calculate the final abundances at 20 different irradiation times corresponding to 20 values of the number n_{cap} of neutrons captured by the seed nuclei during the r-process. These values are evenly distributed in the $10 \leq n_{cap} \leq 150$ range (for full details of the model, see Goriely and Arnould, 1996). We are thus left with some 200 different time-dependent events. Note that these astrophysical conditions have been chosen in order to cover a large range of possible r-process paths. Paths closer to the valley of β-stability, i.e. $S_a^0 \gtrsim 3.4$ MeV, are not included, because they require very large (and likely unrealistic) irradiation times (larger than about 30 s) in order to produce the $A > 132$ nuclei. The nuclear mass predictions of Aboussir et al. (1995) and the β-decay and one-neutron β-delayed emission rates of Tachibana et al. (1990) are used in the r-process calculation.

The elemental abundance distribution in the $55 \leq Z \leq 80$ range resulting from a random superposition of some 40 events out of the 200 defined above is shown in Fig. 1. The agreement between the calculated and observed abundance distributions is seen to be surprisingly good, almost all the observed abundances being reproduced within the error bars. Note that the predictions are independent of the mode of random selection of the 40 different events.

As demonstrated in Fig. 2, the good *local* agreement exhibited in Fig. 1 between the observations and our predictions clearly does not imply a satisfactory agreement with the *global* solar system content of r-nuclides. Neither the position, nor the width or height of the r-process peaks fit the solar pattern. Such a result is of course expected since the solar system r-abundance distribution can only be matched by a specific superposition of events which is far from being random (e.g. Goriely and Arnould, 1996; Goriely, 1997). Moreover, it is well known that the solar r-abundance distribution originates from r-process paths in the $2 \lesssim S_a^0[\mathrm{MeV}] \lesssim 3$ range. An equal contribution of lower S_a^0-value r-process events tends to broaden the r-process peaks[2], as well as to shift their location to lower A-value. This effect is observed in Fig. 2.

[1] In the canonical r-process model, the astrophysical events are characterized by the parameter $S_a^0[\mathrm{MeV}] = (34.075 - \log N_n[\mathrm{cm}^{-3}] + 3/2 \log T_9)\ T_9/5.04$, where T_9 is the temperature expressed in billion degrees, and N_n is the neutron number density. The corresponding r-process path in the (Z, N) plane is defined by $S_a^0 = S_{2n}(Z, N)/2$, where S_{2n} is the two-neutron separation energy of nucleus (Z, N) (for more details, see e.g. Goriely and Arnould, 1992)

[2] Note that, in contradiction to a frequent claim, the width of the r-process peaks does not demonstrate that a small number of r-process events have contributed to the solar system content. An infinite number of events in the $2 \lesssim S_a^0[\mathrm{MeV}] \lesssim 3$ range would equally lead to the same typical width of the solar r-process peaks.

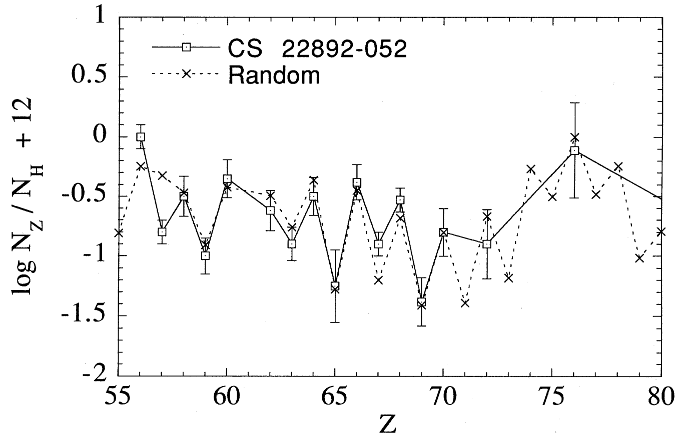

Fig. 1. Elemental abundances N_Z (relative to the H abundance N_H) in the $55 \leq Z \leq 80$ range obtained from a random superposition of r-process events belonging to the set defined in the main text. The abundances of r-elements observed in CS 22892-052 (Sneden et al., 1996) are also represented with their corresponding error bars.

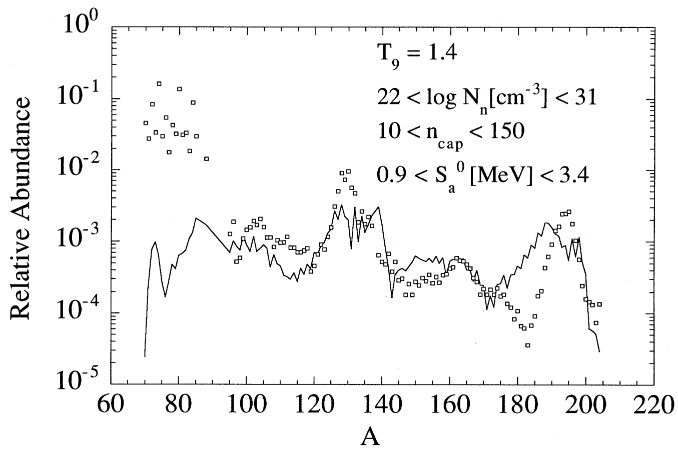

Fig. 2. Comparison between the solar system r-process abundance curve (Käppeler et al., 1989) and the distribution predicted by the random superposition of events leading to Fig. 1. Both distributions are arbitrarily normalized.

One might wonder if the conclusion drawn above that the observations in CS 22892-052 do not necessarily imply a global solar system mix of r-nuclides is not just resulting from the non perfect match of the predictions and the observations appearing in Fig. 1. A fully rigorous proof that this is in fact *not* the case cannot be provided. However, one way to tackle this question is to examine if the calculated distribution in Fig. 1 can be made significantly closer to the CS 22892-052 observations by replacing our choice of random events leading to Fig. 1 by a superposition of events providing the best fit to the solar r-nuclide distribution. The result of this test is found in Figs. 3 and 4. The adopted fitting procedure is described by Bouquelle et al. (1996). The isotopic fit is seen to be relatively good in the whole $70 \leq A \leq 204$ range and involves principally $2 \lesssim S_a^0[\mathrm{MeV}] \lesssim 3$ r-process events, this results being similar to the analysis of Goriely and Arnould (1996). While the predictions of Fig. 4 are by far closer to the whole solar system distribution than those of Fig. 2, it is hard to single out from a comparison between Figs. 1 and 3 which selected set of events really accounts better for the CS 22892-052 observations. We thus confirm our previous conclusion: the observations of CS 22892-052, while indeed being remarkably close to the solar pattern, *do not demonstrate* that the r-process heritage of that star for all the $A \geq 70$ nuclei is necessarily solar.

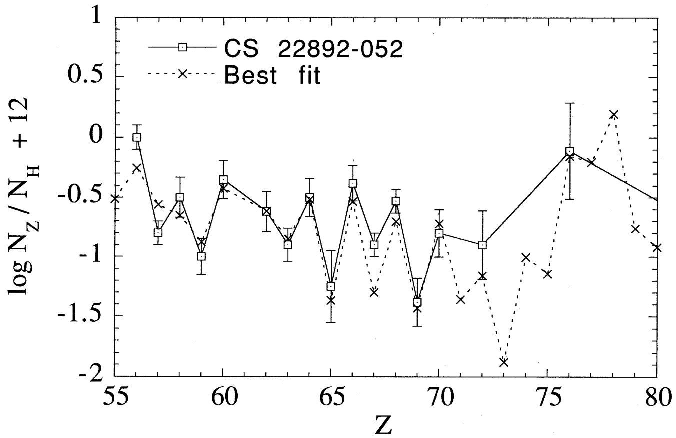

Fig. 3. Same as Fig. 1, but the selected r-process events are those leading to Fig. 4.

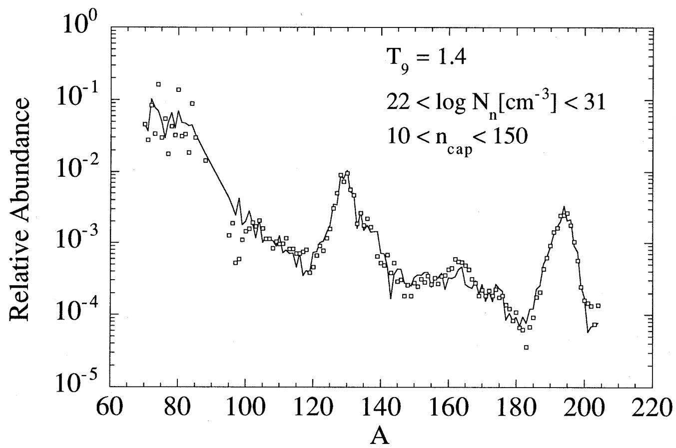

Fig. 4. Same as Fig. 2, but the selected r-process events provide the best fit to the whole solar system r-nuclide abundance.

This conclusion reflects the fact that the pattern of r-abundances in the $56 \leq Z \leq 76$ range is mainly governed by nuclear physics properties along the different r-process paths rather than by specific astrophysical situations. In order to enlighten this statement, let us assume that all the isotopes of the $56 \leq Z \leq 76$ elements that are not bypassed by the r-process are just produced with equal abundances. In such conditions, the abundance of an element is simply proportional to the number of stable non-bypassed isotopes. This artificial and simplistic abundance distribution reproduces remarkably well the observations, as seen in Fig. 5. This result explains why the random distribution of r-process events considered in constructing Fig. 1 agrees so well with the observations. The clearest deviations between the predictions and observations are obtained in the Ba and Os regions. This is attributable to the N = 82 (or/and Z = 50) and N = 126 shell effects, which tend to increase the abundances with respect to those of the off-shell elements. Some deformation effects might also alter the predictions from our simplistic model. Also note that the Ba region raises some specific nuclear problems, the N = 82 and Z = 50 shell closures making this region highly dependent on uncertainties in the nuclear mass and β-decay rate predictions.

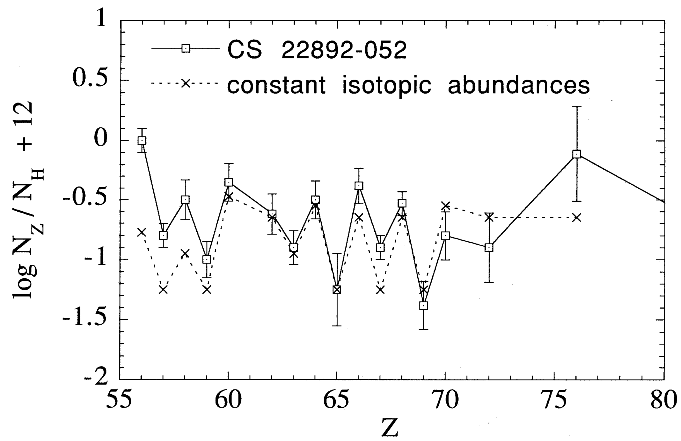

Fig. 5. Comparison of the elemental abundances in the $55 \leq Z \leq 80$ range observed in CS 22892-052 with values obtained under the assumption that the abundance of each of these elements is proportional to the number of its stable isotopes that are not bypassed by the r-process.

Even if the patterns of abundances shown in Figs. 1 and 3 are dominated by nuclear physics properties, other agents might contribute to the deviations of the predictions from the observed abundances. In particular, it has to be recalled that the theoretical abundances do not rely on any astrophysical background. Moreover, some contribution to the CS 22892-052 abundances from the s-process cannot be excluded, especially in the Ba region[3]. In this respect, it is of interest to mention the analysis of the classical metal-poor subgiant HD 140283 ([Fe/H]=–2.7) by Magain (1995), who concludes that its Ba isotopic composition is fully compatible with an s-process origin. Similarly, the ultra-metal-poor stars CS 22948-27 ([Fe/H]=–3.2) and CS 29497-34 ([Fe/H]=–3.5) show large Ba and La overabundances with respect to Eu (Barbuy et al., 1997). This result might also reflect an s-process contribution to the heavy elements content of very metal-poor stars.

[3] Note that the solar r-process contribution to the Ba and Ce elements is quite uncertain, because of the ill-defined s-process contribution to their main isotopes (Goriely, 1997). The claim that CS 22892-052 has a solar r-process abundance pattern in the Ba region may thus be quite meaningless.

3. Conclusion

This Letter analyses critically the quite classical claim that CS 22892-052 has been contaminated with a full solar mix of all the $A \geq 70$ r-nuclides. We conclude that this interpretation may be valid indeed, but is by far *not the only possible one*, as the observations in the limited $56 \leq Z \leq 76$ range are equally compatible with a mix that does not fit the solar one outside the observed domain. We assign this ambiguity to the fact that the observed CS 22892-052 pattern of abundances reflects primarily nuclear physics properties, and not one or another specificity of a blend of r-process events.

In such conditions, it is still not possible to make a final choice between the following two possibilities: (1) the available CS 22892-052 observations demonstrate that the r-process yields are almost perfectly solar irrespective of the mass and metallicity of the producing star (supernova). This invariance would imply that the relative r-nuclidic abundances are not influenced by the galactic chemical evolution effects, or (2) the whole $A \geq 70$ r-process abundance pattern is indeed affected by chemical evolution effects even if invariance in the $56 \leq Z \leq 76$ range is guaranteed by nuclear properties.

As a consequence of this ambiguity, the development of a cosmochronometry based on the Th content of CS 22892-052 remains highly insecure. In fact, case (2) would largely invalidate the conclusions drawn in this respect by Cowan et al. (1997). Obviously, a clarification of the present situation might come from further analyses of the r-process content of ultra-metal-poor stars, especially if abundances can be derived for the elements making the peaks in the solar r-process abundance distribution. As seen in Figs. 1 and 3, new observations, especially around Os, could help constraining the set of events that could have been responsible for the CS 22892-052 enrichment in r-nuclides.

In addition to the unresolved ambiguity defined above, the abundances measured in CS 22892-052 also exhibit some puzzling features. These are mainly the large Eu enrichment with respect to Fe and the C-rich nature of that star. This last property is not straightforwardly compatible with the contamination by an exploding massive star, which is generally considered as the privileged production site of the r-nuclides in spite of the difficulties of the present models (Takahashi and Janka, 1997)

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