

# Effects of the s-process on Fe-group elements in meteorites

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**Abstract.** In the present paper we investigate the possible connection between *s*-process nucleosynthesis occurring during the asymptotic giant branch (AGB) phase of low-mass stars (LMS) and the isotopic anomalies of the “Fe-group” elements observed in several macroscopic samples of meteorites or in grains formed as circumstellar condensates (hereafter CIRCONs). The available measurements of chromium, iron, and nickel are well reproduced by stellar models, which account for the largest shifts in the heaviest isotopes of each element: in particular <sup>54</sup>Cr, <sup>58</sup>Fe, and <sup>64</sup>Ni. Moreover, many circumstellar condensates reflect <sup>50</sup>Ti excesses and some production of <sup>46,47,49</sup>Ti, as predicted by slow-neutron captures in AGB stars. Nevertheless, some difficulties are found in comparing theoretical calculations of *s*-process nucleosynthesis with calcium, silicon, and zinc isotopic anomalies.

## 1. Introduction

The production of elements generally considered to be members of the iron-group (such as Ti, Cr, Fe, Ni, and Zn) is commonly attributed to supernovae (SNe), both core collapse and SNeIa. The isotopes of these elements can now be traced in pristine meteorites with high accuracy, as in the last decades several analysis techniques have been developed allowing to measure anomalies for the abundances of elements and isotopes at the level of a few parts in ten thousand ( $\epsilon$  units). These isotopic effects are common in calcium-aluminum-rich inclusions (CAIs) in meteorites, but are also wide spread at lower levels in “bulk” samples of different groups of meteorites. In this context, we suggest that slow neutron captures, the so-called *s*-process occurring in the asymptotic giant branch phases (AGB) low mass stars (LMS), modify the original abundance of these elements collected from the interstellar medium by the star, by adding more neutrons, thus altering the isotopic admixture in favour of heavier isotopes [1].

In order to obtain a direct comparison with the meteoritic measurements, the enrichment factors  $E^\odot(i, k)$  for isotopic abundances of the “Fe-group” elements are calculated as follow:

$$E^\odot(i, k) = \left[ \left( \frac{N(i)}{N(k)} \right)^* / \left( \frac{N(i)}{N(k)} \right)^\odot \right] - 1, \quad (1)$$

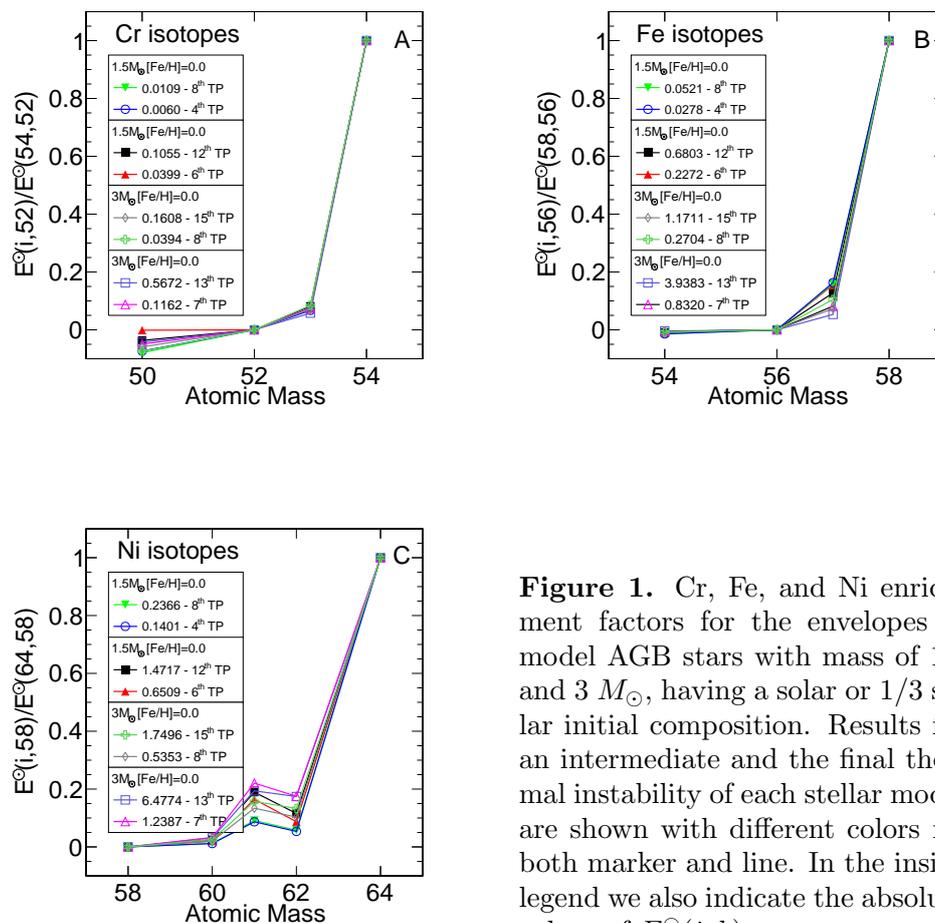
where an initial solar abundance [2] was assumed and “*k*” is a reference nucleus which is of high abundance. The composition of the envelopes of 1.5 and 3  $M_\odot$  model stars, for solar and



1/3 solar metallicity, were computed till the end of the AGB phase, using our post-process nucleosynthesis code NEWTON and adopting an extended  $^{13}\text{C}$ -pocket as described in [3].

## 2. Cr, Ni, and Fe

The enrichment factors in isotopic abundances for Cr, Fe, and Ni are shown in panels A, B, and C, respectively of Figure 1. The *s*-process nucleosynthesis calculations suggest a large positive shift for  $^{54}\text{Cr}$ ,  $^{58}\text{Fe}$ , and  $^{64}\text{Ni}$  (representing the heaviest stable isotope of each element), while only limited variations are expected for other nuclei and in some cases, as for  $^{50}\text{Cr}$  and  $^{54}\text{Fe}$ , even a negative shift is predicted.

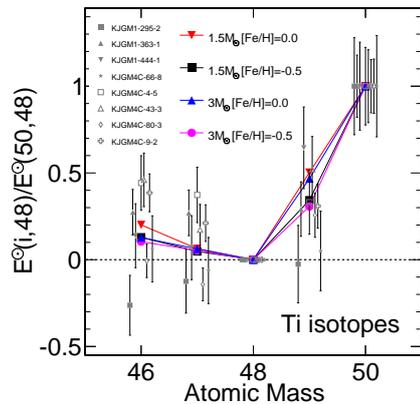


**Figure 1.** Cr, Fe, and Ni enrichment factors for the envelopes of model AGB stars with mass of 1.5 and 3  $M_{\odot}$ , having a solar or 1/3 solar initial composition. Results for an intermediate and the final thermal instability of each stellar model are shown with different colors for both marker and line. In the inside legend we also indicate the absolute values of  $E^{\odot}(i, k)$ .

Starting from the comparison of results in Figure 1 with data measured from those samples which are associated with AGB stars (e.g. [4] in the case of Ni), our suggestion is that the “iron group” elements mentioned above were originally made in SNe, but their products were subsequently reprocessed in AGB stars, resulting in the observed effects. Moreover, it turns out that the magnitude of the enrichment factors is dependent on the size of the  $^{13}\text{C}$ -pocket, the stellar mass, the initial composition, and the stage of evolution of the star.

## 3. Titanium isotopes

In Figure 2 we collect a wide selection of Ti isotopic data on main stream CIRCONS compared to AGB *s*-process patterns. We observe that slow neutron captures calculations show a typical “J” pattern [1, 5] because of smaller  $E^{\odot}(46, 48)$  shifts with respect to  $E^{\odot}(50, 48)$  ones.



**Figure 2.** Comparison between Ti isotopic data (grey points) on main stream CIRCONS ([6], [7], and [8]) and  $s$ -process predictions in AGB-LMS. Markers and lines of different colors refer to calculations regarding stars of 1.5 and 3  $M_{\odot}$ , solar and 1/3 solar metallicity. For the sake of comparison, measurement data and  $s$ -process theoretical predictions are normalized to  $\delta(50, 48)$  and  $E^{\odot}(50, 48)$ , respectively.

There are abundant isotopic data (see grey dots in Figure 2 and references therein) on titanium and many circumstellar condensates reflect  $^{50}\text{Ti}$  excesses and some production of  $^{46,47,49}\text{Ti}$ , as suggested by AGB neutron captures. From these observations we conclude that a large fraction of these grains show clear evidence of  $s$ -processing. However, there are also cases showing a disagreement with higher shifts in lighter nuclei, giving the image of a “V” pattern.

#### 4. Conclusions

We computed the effects of slow neutron capture nucleosynthesis on Cr, Fe, and Ni through 1.5  $M_{\odot}$  and 3  $M_{\odot}$  AGB models, adopting solar and 1/3 solar metallicities. All cases produce excesses of  $^{54}\text{Cr}$ ,  $^{58}\text{Fe}$ , and  $^{64}\text{Ni}$ , while the other isotopes are little altered; hence, the observations made in recent years in meteorites may be explained by AGB processing.

The case of titanium is roughly similar and it is possible to correlate the  $s$ -processing predictions with data from those circumstellar condensates that are usually associated with AGB sources (those belonging to the so-called “main stream”).

On the other hand, concerning the effects of  $s$ -processing on silicon, calcium, and zinc, the scenario is more complex. For Si, the main effects are due to variations in the local ISM from different SNe sources. Calcium still represents an open problem because calculations suggest large anomalies on  $^{46}\text{Ca}$ , but no observations support this. In general, the Ca shifts in  $s$ -processing are relatively weak as compared to Ti, Cr, Fe, and Ni. At the end, no clear explanation are possible for Zn because only limited measurements are available and they don’t show large shifts for  $^{68}\text{Zn}$  as predicted by nucleosynthesis calculations.

#### 5. Acknowledgments

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