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# r-process observations

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**Abstract.** The r-process nucleosynthesis in the Universe is constrained by observations of chemical abundances of the Solar System and those of old stars that should record the products of the r-process events in the early Universe. This review provides a brief overview of the observational technique to determine chemical abundances of stars. Targets of observations are stars in different populations of the Milky Way Galaxy and surrounding dwarf galaxies, providing different kind of constraints on the understanding of the r-process. Recent progress in observational studies to identify the r-process sites are also reviewed.

## 1 Introduction

The r-process is a major source of heavy neutron-capture elements in the universe. This process should be related to rare explosive events with extreme conditions, like neutron star mergers or some sort of supernova explosions. A goal of current observational studies on the r-process is to identify the astrophysical site of this process, or at least to provide useful constraints on its characteristics.

Measurements of heavy neutron-capture elements in explosive events by optical spectroscopy to measure spectral lines, or by observations of $\gamma$-ray from radio-active nuclei, are desired to identify the sites of the r-process and to determine the production yields. There is, however, no definitive detection of heavy neutron-capture elements enhanced in promising r-process sites. Measurements of heavy elements in absorption spectra of supernova remnants were attempted, resulting in no clear detection [1]. Very recently, a merger of binary neutron stars was identified both by gravitational wave and electromagnetic waves including $\gamma$-ray and optical light [2][3]. The excess of the red and near-infrared flux in the observed afterglow is suggested to be a result of ejection of lantanides, which are much more opaque in the optical range than usual metal like Fe [4]. Detection of some neutron-capture elements in optical spectra of the afterglow is also suggested, though it contains large uncertainties, and further measurements in the near future and modeling of the events are desirable.

On the other hand, observational constraints on the r-process currently available have been indirectly obtained from abundance measurements for solar-system material and stars in the Milky Way and nearby galaxies.

## 2 Constraints from solar-system abundances

The elemental abundances of solar-system material have been used as the most important reference to compare the prediction of r-process models (e.g., [5, 6]).

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The elemental abundances of solar-system material are determined from chemical analysis of meteorites and analysis of the solar spectrum. Recent measurements by the two methods exhibit fairly good agreement for heavy neutron-capture elements in general [7]. In particular, the recent updates of atomic line data, including the effect of isotope shift and hyperfine splitting, have been making large contribution to the improvements of solar atmospheric abundances (e.g., [8]).

An advantage of the analysis of meteorites is that it can determine isotope ratios, which provide much stronger constraints on the models of neutron-capture processes than elemental abundance ratios. It should be noted that isotope ratios of a few heavy elements (e.g. Eu) have been determined by the detailed profile analysis of spectral lines which are affected by hyperfine splitting depending on isotopes (e.g. [9, 10]).

The heavy neutron-capture elements with mass number ($A$) larger than $\sim 70$ in the solar-system material are originated from both the s- and r-processes. The contributions of the two processes are well identified by the existence of abundance peaks corresponding to the neutron magic numbers (50, 82, and 126), appearing slightly different mass numbers due to the difference of the reaction paths on nuclear chart between the two processes.

Since the abundances of s-process yields are basically determined by reactions along stable nuclei, modeling of this process is better established than that of the r-process. There are dozens of nuclei which are never produced by the r-process because they are shielded by other stable nuclei from $\beta$-decay of neutron-rich unstable nuclei ("s-only" nuclei). Models of the s-process are calibrated by the abundance of these s-only nuclei, which enable us to estimate the fraction of abundances produced by the s-process for other nuclei [11]. The r-process component of each isotope is obtained by subtracting the s-process component from the abundance of each isotope for solar-system material.

Hence, the uncertainty of the s-process models affects the accuracy of the estimates of the r-process abundance patterns of solar-system material. This is significant in the nuclei in which s-process component is dominant, because a small error in the estimate of the s-process component could results in a large error in the obtained r-process fraction. An example is Pb, for which the s-process component is estimated to be as large as 80% in solar-system material. This makes it difficult to constrain the models for production of heaviest stable nuclei by the r-process [12].

## 3 Abundance patterns of metal-poor stars

The solar abundances discussed in the previous section are determined by numerous nucleosynthesis processes in the long history of the Milky Way before the formation of the Sun at around 4.6 billion years ago. Hence, the r-process abundance pattern, which is separated from the s-process component, should be regarded as a sum of the r-process yields by a large number of events.

By contrast, measurements of heavy neutron-capture elements in very metal-poor stars provide unique constraint on the r-process models. Such stars are regarded as old low-mass stars formed in the early stage of the Milky Way evolution, at which the metallicity of gas clouds was generally very low. Metal-poor stars formed from such clouds should record nucleosynthesis yields of only a small number of events. In the most extreme cases, the abundance of neutron-capture elements could be a result of a single event. The abundance patterns of such objects are very useful references to study the yields of the r-process and their possible variation.

A remarkable result obtained by the intensive spectroscopic studies for very metal-poor stars in the past two decades is the discovery of large star-to-star scatter in abundance ratios of neutron-capture elements. Figure 1 shows the Mg and Eu abundances as a function of metallicity (Fe abundance)[1]. Here we adopt Eu as an indicator of the r-process yields.

[1] Abundance ratios of two elements are given as $[A/B] = \log(N_A/N_B) - \log(N_A/N_B)_\odot$. Here "Fe abundance" means [Fe/H].

We find a clear correlation with little scatter in abundances between Mg and Fe, both of which are yields of massive stars and their supernova explosions in the low metallicity range. Contributions of type Ia supernovae are significant at high metallicity, that result in a change of the slope in [Fe/H]$> -1$ (see next section). By contrast, the Eu abundances show large star-to-star scatter at low metallicity. Metal-poor stars having high Eu abundances are interpreted as objects that were born from gas clouds significantly polluted by an r-process event in the early Galaxy. This indicates that the gas clouds were not chemically homogeneous due to insufficient mixing in the early Galaxy, and the r-process events should be independent of those yielding Fe, i.e. usual core-collapse supernovae.

The detection probability of Eu is lower in metal poor stars having low Eu abundances, because Eu spectral lines are quite weak in such objects. Given this bias in the sample, Eu-enhanced stars are rare objects. This indicates that the r-process events are rare, but each event could provide the Universe with a large amount of Eu.

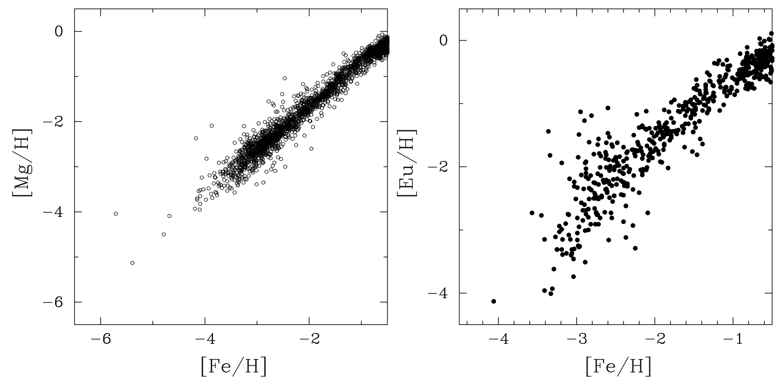


**Figure 1.** Abundance ratios of Mg and Eu with respect to Fe. Abundance data are taken from the SAGA database [13].

Eu-enhanced metal-poor stars are ideal objects to study the abundance patterns produced by the r-process. A difficulty in the spectroscopic measurement of neutron-capture elements is the weakness of spectral lines of these elements and severe contamination of features of other elements (e.g., Fe, Ti) and molecules. This difficulty is reduced in the analysis of metal-poor objects having excess of r-process elements including Eu. As a result, many spectral lines of neutron-capture elements that are not measured even for the solar spectrum are used in the analysis of Eu-enhanced metal-poor stars.

A remarkable result obtained for Eu-rich stars is that abundance patterns of neutron-capture elements of these stars are very similar to that of the r-process component in solar-system material [14, 15]. The agreement is in particular evident in elements from the second and third peaks corresponding to the neutron magic numbers 82 and 126 (Ba-Pt). We note that the measurements of the elements at the second r-process peak (Te-Xe) is very limited because there is no useful spectral lines in the optical range [16].

This result indicates that the r-process produces neutron-capture elements with similar abundance patterns in every event. This phenomenon is called the universality of the r-process, and has a large impact on understanding of the process, because it could be a strong constraint on r-process models that predict more or less variation of abundance ratios depending on model parameters like electron fraction and entropy.

It should be noted that the abundance patterns of light neutron-capture elements (e.g., Sr, Y) are also similar between such Eu-enhanced stars, but they show some deviation from the solar r-process pattern [15]. Moreover, there are many metal-poor stars that have low abundances of heavy neutron-capture elements like Eu, but have large excess of light ones [17]. A recent study [18] has revealed that metal-poor stars have wide variations in the abundance patterns from light to heavy neutron-capture elements including intermediate ones (e.g., Mo, Pd). This suggests that there are at least two origins of the r-process component of light neutron-capture elements in the universe, and both were effective even in the early Galaxy.

## 4 Abundance trend and scatter

The trends and scatter in the Eu abundance distribution also provide a useful constraint on the origins of the r-process. The enrichment of an element depends on the timescale of the corresponding nucleosynthesis event. For instance, as found in Figure 1, Mg abundance ratios are systematically higher than Fe abundance ratios by 0.3–0.5 dex in the low-metallicity range. This reflects the yields from massive stars and their supernova explosions. On the other hand, a large fraction of Fe in the solar-system are originated from type Ia supernovae, whose time-scale is longer than core-collapse supernovae of massive stars.

Although the scatter of Eu abundance ratios in metal-poor stars is large, the existence of Eu-enhanced objects at low metallicity suggests that the time-scale of the r-process is not long. This was regarded as a difficulty in the scenario of merger of binary neutron stars, for which timescale of about 100 million years is expected [19].

Recent chemical evolution models ([20, 21]), however, predict that neutron-capture elements could be enhanced by merger of binary neutron stars even at low metallicity, including accretion of small stellar systems originated from mini-halos in the formation process of the Milky Way halo. In such small systems, star formation, and as a result metal enrichment, should have proceeded more slowly than in large systems. Hence, it takes relatively long time in formation of very metal-poor stars, some of which could have suffered from the r-process events by neutron star mergers.

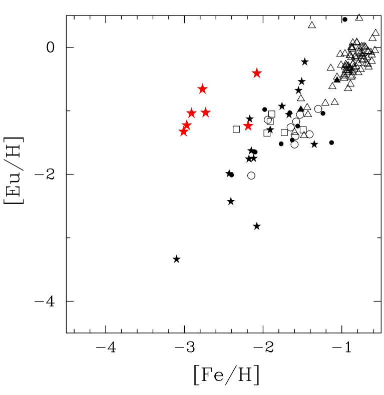


**Figure 2.** Eu abundance ratios of stars in dwarf galaxies as a function of metallicity ([Fe/H]). Abundance data are taken from the SAGA database [13]. Different symbols mean stars in different galaxies (open triangle: Fornax; open circle: Carina; filled circle: Sculptor; open square: Draco; filled triangle: Leo I; smaller stars: Ursa Minor; large red stars: Reticulum 2). A typical error of [Eu/H] is 0.2 dex, although it depends on data quality and strength of spectral lines. The seven objects in Reticulum 2 are very metal-poor stars that show large excess of Eu.

Small stellar systems are found as satellite dwarf galaxies in the present Milky Way Galaxy, which have wide range of stellar mass ($10^3$–$10^7$ solar masses). They could be survivors of small stellar systems formed in the very early phase of the Milky Way formation. Such small stellar systems could be significantly affected by a small number of nucleosynthesis events.

Figure 2 compiles the Eu abundances measured for dwarf galaxy stars. As in the case of field halo stars, the Eu abundances increase with the increase of Fe abundances. The number of stars with low Eu abundances at low metallicity ([Fe/H]$< -2$) is small, compared to field halo stars in Figure 1, but this should be because of the detection limit of Eu lines in dwarf galaxy stars (see Section 3).

Tsujimoto & Shigeyama [22] pointed out that dwarf galaxy stars with $-2 \lesssim$ [Fe/H] $\lesssim -1$ have almost constant [Eu/H] values, independently of metallicity. Subsequent observational studies [23] for dwarf galaxies also support this feature. The r-process event should have supplied a large amount of neutron-capture elements, but should be a quite rare event compared to supernova explosions that supply Fe and other metals. In larger stellar systems, as in the bulk of the Milky Way halo, more than one events of r-process should have occurred, as well as supernova explosions, resulting in a correlation between Eu and Fe abundances. Neutron star mergers could be the rare events corresponding to the r-process.

Among the faintest dwarf galaxies, called Ultra Faint dwarf Galaxies, Reticulum 2 is a unique object, in which very metal-poor stars ([Fe/H]$< -2.5$) show large excess of Eu ([Eu/Fe]$> +1$) [24][25]. Such Eu-enhanced stars are known in the Milky Way halo as mentioned above, and their fraction is estimated to be 3–5% (e.g., [26]). The studies for Reticulum 2 measured elemental abundances for nine stars and found seven of them have high Eu abundances. The remaining two stars have the lowest metallicity ([Fe/H]$< -3$). This suggests that the gas clouds in the whole galaxy was polluted by a single event of the r-process in the early phase before forming very metal-poor stars with [Fe/H]$\sim -3$. Accretion of such stellar systems could be the origins of the r-process enhanced very metal-poor stars in the Milky Way halo.

The Eu abundances found in faint dwarf galaxies, including Reticulum 2, are [Eu/H]$\sim -1$. This corresponds to the Eu/H mass ratio of $10^{-10.3}$. Assuming the original mass of hydrogen gas in the galaxy to be $10^6$ solar masses, the Eu mass provided by the r-process is estimated to be $10^{-4.3}$ solar masses. This is comparable to the Eu mass expected to be produced by a single event of merger of binary neutron stars and a magnetrotationally driven supernovae ($10^{-4.5}$–$10^{-5}$ [27]). Assuming the contribution of r-process is only once in individual galaxies, the event rate is 1000-2000 times lower than usual supernovae, as 1000-2000 supernova explosions are expected in a galaxy with a stellar mass of $10^6$ solar masses [24]. This rate is also consistent with that expected for neutron star mergers.

## 5 Summary and concluding remarks

Recent observational studies for very metal-poor stars in the Milky Way halo and dwarf galaxies have been providing useful constraints on the origins and nature of the r-process. Further observations of a large number of stars in individual dwarf galaxies are desirable for better understanding of the astrophysical sites of the r-process and its role in chemical evolution. Such observations covering fainter objects in dwarf galaxies will become possible with new generation large telescopes like TMT, E-ELT and GMT with high-resolution spectrometers. More direct evidence of the r-process will be obtained by future observations of mergers of binary neutron stars following the first detection of the gravitational wave and corresponding electromagnetic waves for GW 170817.

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