Formation of elements heavier than Iron

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ABSTRACT
Scientists have long tried to figure out how the heavier element is made. The natural abundance of heavy element is thought to be explained by neutron star mergers. With intense heat and abundant neutrons, is predicted to be the most likely cause of the abundance of certain elements on Earth. Here we sought to identify how the heaviest nuclei naturally form along the neutron drip line. Much of the work on neutron star mergers is hypothetical, but observations of stellar events and data from particle accelerators contribute significantly to the available information. The available data suggest that heavier elements form in similar proportions to the modeled elements in the rest of the universe. The data support the hypothesis that these heavy elements are produced by the r-process of neutron star mergers. More powerful accelerators are being built to study these processes, and the amount of existing data should increase dramatically with each advancement in accelerator technology.

1 INTRODUCTION

The lightest element in the universe was born shortly after the big bang. The heavier elements, down to iron, were later forged. Most of these "heavy elements" are made by neutron-capturing atomic nuclei. This neutron capture process comes in two forms: fast process *(r-process)* and slow process *(s-process)*. The s-processes mainly produce light elements up to lead and bismuth , while the r-processes usually produce elements as heavy as uranium, which is found in the nuclei of galaxies. When neutron stars merge, they release a few percent of their mass as neutron-rich material. This ejected mass is transformed into a radioactive fireball of the heaviest element within just one second by the r process. These elements scatter in interstellar space, seeding clouds of gas and eventually forming stars and planets with the elements they contain.

2 THEORY

We can identify 3 basic processes by which the heavy nucleus continuously adds protons or neutrons. These are given as below

- S-process(slow neutron)
- R-process(rapid neutron)
- P-process

Neutrons get capture into lightnuclei producing neutron-rich nuclei, but these nuclei production rate are depend on the rate at which neutrons are absorbed by light nuclei. Slow neutron capture produces nuclei which are near to the β stability valley, however the fast capture of initially produce very neutron-rich radioactive nuclei and then eventually it gets collapse towards the β stability valley. Some of the cores could be built in multiple processes which are shown in Figure (1). Proton gets trapped to light nuclei which goes to produce only proton-rich nuclei. For small neutron velocities v, i. e. energies up to a few tens of keV, the capture cross section of neutron varies as $\sigma \propto v^{-1}$. Therefore the product σv is approximately constant for thermal energy. At a temperature of about $30keV$, the thermal velocity of neutrons is about $3 \times 10^8 cms^{-3}$. The nuclear lifetime for neutron capture is

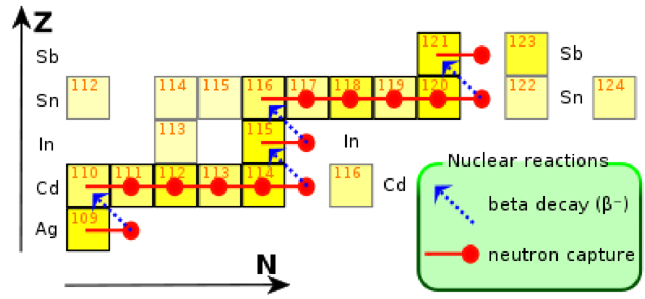

Figure 1. β decay and neutron capture

$$\tau_n \sim \frac{1}{n_n \sigma v} \sim \frac{3 \times 10^{17}}{n_n} s \tag{1}$$

s-process timescales are around $10^4 yr$, while r-process timescales are around microseconds order, indicating neutron densities of $10^5 - 10^6 cm^{-3}$ and $10^{23} - 10^{24} cm^{-3}$ respectively.

2.1 S-Process

In nuclear-synthesis, the s-process is a series of reactions which occurs in stars, e.g. AGB stars. If the new isotope is stable, it will eventually undergo into a serieses of mass increases. If it is unstable, β decay will happen, producing the elements with higher atomic number. This is slow process because there is more time for radioactive decay before another neutron is captured. As shown in fig(2), the seed nucleus undergo neutron capture to form isotope with higher atomic mass in the s process.

$$\begin{aligned} {}^{13}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{16}_{8}\mathrm{O} + {}^{1}_{0}\mathrm{n} \\ {}^{22}_{10}\mathrm{Ne} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{25}_{12}\mathrm{Mg} + {}^{1}_{0}\mathrm{n} \end{aligned} \tag{2}$$

Quantitative analysis can be performed on the basic assumption

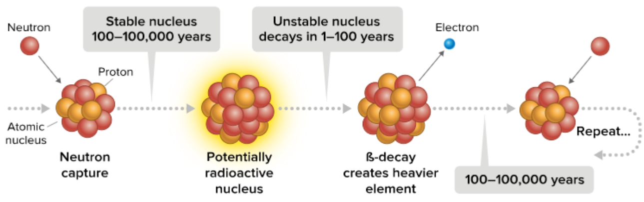

Figure 2. s-process

that the beta decay timescales are all very fast compared to the neutron capture rate, except for the magic number nuclei. N_A can represent the abundance of core A without reference to Z, and the abundance of radioactive nuclei can be neglected. The frequency differential equation is

$$\dot{N}_A = -\langle\sigma v\rangle_A n_n N_A + \langle\sigma v\rangle_{A-1} n_n N_{A-1} \tag{3}$$

where $\langle\sigma v\rangle_A$ is the thermal average of each nucleus A. Assuming $\sigma \propto v^{-1}$, you can write $\langle\sigma v\rangle_A \approx v_T \sigma_A$. where v_T is thermal speed. Definition of Neutron Dose τ by $d\tau v_T n_n dt$ Obtained as

$$N'_A = -\langle\sigma v\rangle_A N_A + \langle\sigma v\rangle_{A-1} N_{A-1} \tag{4}$$

This equation can only be solved with proper boundary conditions. Exposure τ varies from event to event, so each S-process event yields a different frequency pattern. A commonly used approximation is that the event probability is equal to $Ge^{-\tau/\tau_0}$ and the parameters are G and τ_0. The abundance pattern will be

$$\begin{aligned}\sigma_A N_A = &\int_0^\infty G\lambda_A e^{-\tau/\tau_0} \frac{(\lambda_A \tau)^{m_A - 1}}{\zeta(m_A)} e^{-\lambda_A \tau} d\tau \\ &= G\left(\frac{\lambda_A \tau_0}{1 + \lambda_A \tau_0}\right)^{m_A}\end{aligned} \tag{5}$$

The s process is in contrast to the r process, in which successive neutron captures are rapid and occur faster than beta decay occurs. The r process dominates in environments with higher free neutron flux. Produces heavier elements and neutron-rich isotopes than the s process.

2.2 R-Process

The r-process is a series of nuclear reactions, which are responsible for the formation of half of elements heavier than iron. The r-process basically creates the most neutron-rich stable isotope of each heavy elements. Abundant peaks of the r process have mass numbers around $A = 82$ (elements Se, Br, and Kr), $A = 130$ (elements Te,I,and Xe), and $A = 196$ (elements Os, Ir). The r-process have the sequence of rapid neutron captures by one or more heavy seed nuclei. It usually begins in the nucleus at the abundances peak centered at ^{56}Fe. The neutron capture must be fast enough in the sense that the nucleus must not undergo radioactive decay (usually by β decay) before another neutron is captured. This sequence can be continue upto the stability limit of increasingly neutron-rich nuclei to suppress neutron determined by short-range nuclear forces. So the r process must occur at the location with a high density of neutrons. So material get ejected from the expanded again core of core-collapse supernovae as part of the nuclei-synthesis of supernova , or decompression of neutron star materials ejected by neutron star merger at kilo-nova. The relative contribution from each of those sources of the r-process element is the topic of recent research.

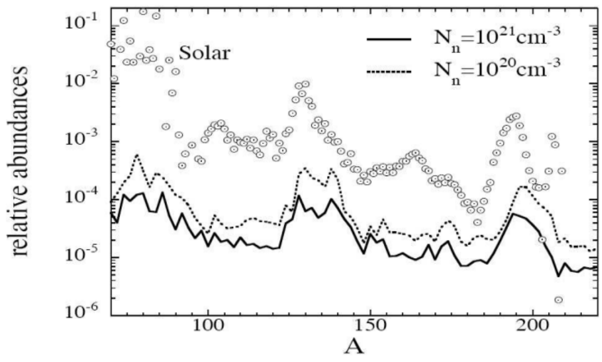

Figure 3. r-process abundances from solar-system with neutron flow approximation.

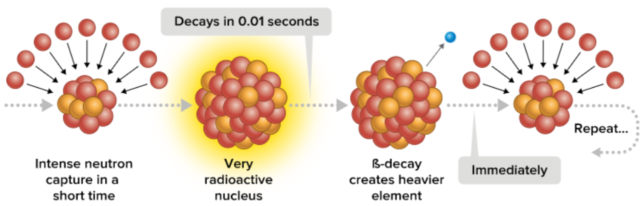

Figure 4. r-process

For this capture, chain at particular Z moves far away from the β-stable neuclei path until the neutron BE becomes very low until further neutron captures get stopped. Then for every charge Z there is a waiting point where β decay must occur in order to continuing the chain to a larger atomic number. The abundance for charge Z will be

$$\dot{n}_Z = \lambda_\beta^{Z-1} n_{Z-1} - \lambda_\beta^Z n_Z \tag{6}$$

Where λ_β^Z is the beta decay rate. The solution of above equations is similar to the s-process which is

$$N_A = \frac{N_0}{\lambda_n^A} = N_0 \left(\sum_Z \frac{\lambda_\beta^{Z,A} \lambda_n^{Z<A}}{\lambda_\beta^{Z,A} + \lambda_n^{Z,A}} \right)^{-1} \tag{7}$$

Where N_0 is the normalization constant.

The r-process source is not totally known. The two competing sites are in Type-II supernovae and neutron star mergers, merging with other neutron stars or compact binary black holes. The latter position, , appears to be more speculative, but neither the existence of such a compact binary nor the merger is known to occur on a less timescale of 10 million years. Models show that the merger would eject 100 times the mass of the Sun's neutron-star material, and produce r-process cores upon decompression. But supernovae do not appear to emit enough neutron to drive at least one effective r-process capable of producing nuclei, which is related to the final magic neutron number.

Basically, the isotopes created by the s-process has a sufficient long half-life compared to other isotopes to allow experiment in lab experiments, However this is not usually the case for the isotopes involved in the r-process. Not true for the stars, especially AGB stars, neutron flux is sufficient to repeat neutron captures every 10–100 years, too slow for r-process , which requires 100 captures per second. The existing heavy isotope as a seed nucleus must be transformed into other heavy nuclei by slow and continuous free neutron capture. In the scenario of the r- process, a seed nucleus of its own is generated, so that this may evolve into a massive star that do not contains a heavy seed nucleus. So r-processes and s-processes account for almost all of the abundances of chemical elements heavier than Fe. A historical challenges have been to find the right physical environment for the timescale.

2.3 P-Process

Proton excess nuclides could be formed by repeatedly adding one or more protons to the nucleus. Such type of nuclear reaction is known as the proton capture reaction where adding protons to the nucleus changes the element nature. Because of chemical nature of elements determined by number of proton present in the nucleus. When the ratio of protons to neutrons changes, producing neutron-poor isotopes. That gave rise to the ideas for the generation of p-nuclei. Free protons would be get captured by heavy nuclei which are already present in the star's plasma. However, such proton would be captured with stable nuclides is not very efficient in producing p-nuclei.

Proton capture at very high proton density is called the rapid proton capture process. These are different from the p- process not only in case for the required high proton densities but also they are very short-lived nuclides and their reaction paths are compared to the proton drip line. Although the p-process could be occur in type-II-supernova explosions, accretion on neutron star surfaces have also been shown to result in type-I-X-ray bursts and produced this type of nuclei.

2.4 Supernovae explosion

The highly massive stars continues the process of consuming the products from last fusion fuel until they developed an extremely hot temperature with densed core of Fe. The nuclear binding energy of the element increases up to $Fe - 56$ which is the most tightly bounded nucleus in our periodic table. The electrostatic force prevents heavier elements than this from being created by fusion at ordinary temperature of star. After $Fe - 56$, heavier elements are created by the process of fission and the fission products are endothermic process which requires energy. The star becomes so dense that they are unable to support its own gravity and the rapid collapse of the core causes shock waves resulting in an intense explosion known as a supernova. The supernova is hotter and more intense than the initial conditions of the star and forms the heavier elements. The resulting explosion sends out a mixture of isotopes of the elements created in the supernova. Stable only in the conditions of the supernova in which these isotopes decay rapidly into the stable elements as it distributed across our galaxy.

2.5 Neutron star merger

What's left of the star after this supernova explosion becomes a neutron star. The remaining matter is very neutron rich and the resulting body is extremely dense. Being so dense, they have a strong gravitational pull. When remnants of two such stellar bodies come close together, this strong gravitational pull causes them draw closer and closer together over time. As they draw closer, they orbit each other, forming a binary system which gradually draw in closer and closer until the stars merge. When the stars come together they release

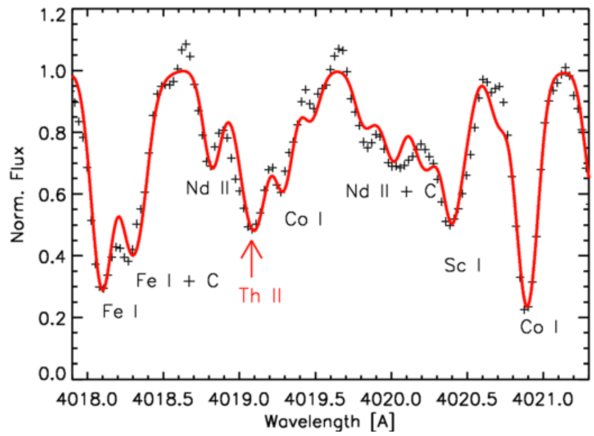

Figure 5. UVES spectrum of a metal-poor giant having the first detection of Th (red line)

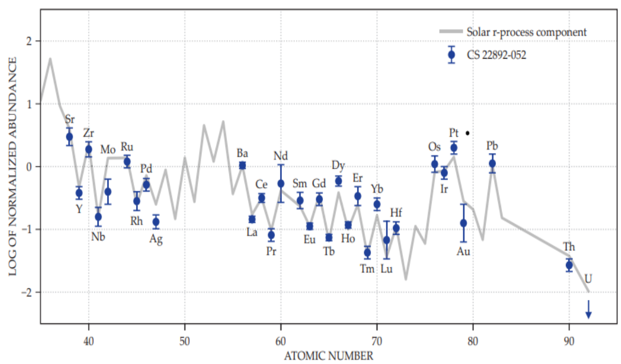

Figure 6. The abundance of r-process in star CS22892-0052 matching with the r-process solar system abundances

energy in various forms including gravitational waves, matter, and light.

3 OBSERVATIONAL DATA AND ANALYSIS

When supernovae explodes , it produces a lot of amount of light and emits as many neutrons. Neutrons get rapidly get captured by other seed nuclei and then it get emitted by the exploding star , creating new nuclei by the 'r' process. In this r process so many neutrons are available, but only a fixed number of neutron can be added to a given nucleus, otherwise the nucleus would becomes radioactive and decays. When nucleus gets "saturated" with neutrons, beta decay occurs and so that it becomes the nucleus of the next elements. Then this new nucleus then absorbs as much neutrons as it can take and when it gets "saturated" then it decays and the cycle begins again repeated way. This type neutrons capture process is called the 's' process which is very slow. Many years may pass in between these neutron collisions process, however in the r-process which represents for "repid" , allowed rapid capture of neutrons. Unlike "s" process which occurs inside the star before get explodes, the "r" process occurs only during the time of star's explosion.

As elements formed from r-process goes toward very heavy like total number of proton and neutron goes to 270, it gets spontaneously

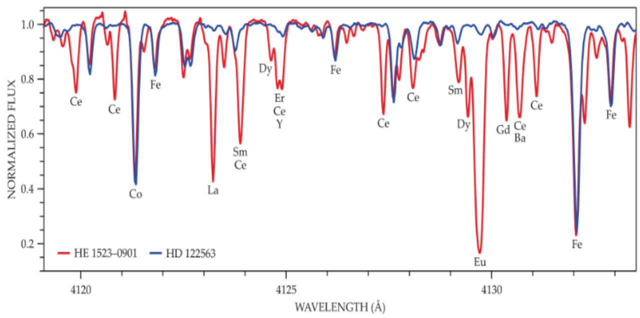

Figure 7. The blue spectrum is for r-process-deficient star HD122563. The red spectrum the absorption lines for rare-earth elements

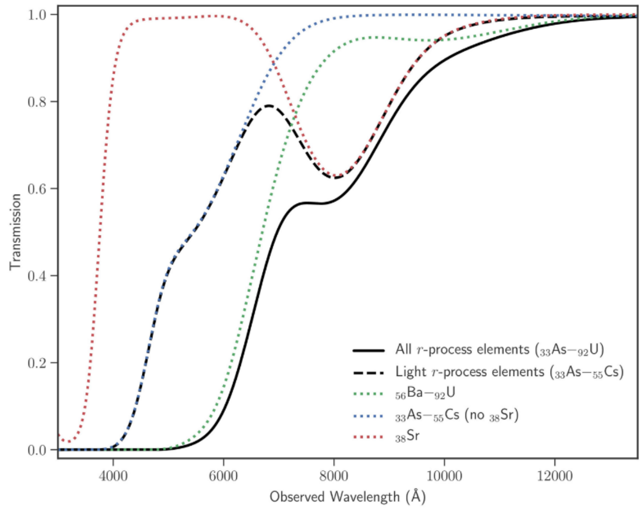

Figure 8. r-process-element transmission spectra

breaks apart via a process known as fission. Neutrons get multiply very rapidly at billion degree temperature, changing from Fe to U in less amount of time(1sec). The elements which are produced are included mostly the trans-uranium elements, which have more protons than uranium. By observing the recent neutron star merging, the astrophysicist tried to determine whether this process is involved in the formation of the heavier element than iron from this merging. So they look at the natural abundance of Europium in the solar system and then compared it with the emissions of the merging event. From the data they have collected they hypothesized that neutron star mergers are basically responsible for the elemental fragments found in the universe. Observational study of two highly r-process rich Metal-poor stars were the first to detected with the heaviest elements such as Th and U. Those elements which are spectroscopically detected in couple of stars as they show weak lines just around $4000A^{\circ}$(see Fig.5).

In $CS22892-052$ star the abundance of r-process occurring elements i.e. Eu which are much more than approx 10 times as the abundance ratio in the Sun relative to that of Fe. In bracket notation This results can be expressed such a way as $[Eu/Fe] > +1.0$. The above figure(7) which compares the absorption spectra of an $r-II$ star with a typical old star and then it showed a strong absorption lines for several rare-earth elements as it shown in figure. As figure (6) describing about the total abundance patterns of r-process elements in r-II stars which is essentially identical to that of the Solar System. This near identity is due to the fact that the $r-I$ and $r-II$ stars which are formed from gas are significantly different from solar system material. Those stars have $[Fe/H]$ values no larger than -1.5 and sometimes as low as -3.5 which is known as metallicity The quantity $[Fe/H]$ describes about the total abundances of elements beyond hydrogen and helium up to and including Fe. Also, $r-I$ stars and $r-II$ stars assumed to be formed early in the cosmic history, whereas the solar system is 4.6billion years old which is relatively younger. The similarity in abundance patterns in such distinguished systems indicating the remarkably rapid r-process behavior.

As ultra fast dwarf(ufd) galaxies are discovered, then the brightest stars are easily get observe using high resolution spectroscope. So that we will get to understand their chemical composition and its properties of material present on it and so that we could know about the evolution of star formation and chemical components. The identification of other r-process-enhanced galaxies will allow us to interpret and analysis the nucleosynthetic products of r-process in the simplest possible way.

4 DISCUSSION

Nuclear fusion creates heavy elements, so that it power up the star and causes star to shine. Those elements which are heavier than iron most of them are produced in environments with free neutron rich environment. When the free neutron is captured by the seed nucleus the heavier radioactive element creates which then decays into a stable heavy species, which is heavier than iron which is known as slow neutron capture process(s-process), mainly happens during the later stages in the evolution of stars of 1 to 10 times mass of sun. However, the s-process is responsible for the formation of only about half of the isotopes beyond iron. The production of the other half requires a rapid neutron capture which is known as the r-process, where the neutron density is high like greater than 10^{20} neutrons/cm^3 so that it will collide with other seed nuclei.

5 CONCLUSION

Here we have explained the existence of the heaviest elements in the proportions in which they occur in our Milky Way. Based upon the expected abundances of the elements, we have concluded that supernovae and neutron star merger are in the production of these elements. As neutron star mergers events are so rare, it is hard to say whether the data collected can be considered to represent typical behavior of a neutron star merger. However, it does seem highly likely that this sort of stellar interaction is the predominant source of r-process nuclei. Based on recent observations and comparisons to the expected values, the matter ejected from the explosion fit the expected values for it's abundance in the material. We have also analysed the absorption spectra of heavy elements in r-process enchanced star in galactic halo and stars in UDF and compared with absorption lines for several rare-earth elements. As more advanced research facilities, are being developed, scientists soon will be better able to replicate the conditions they wish to study and more accurate data will be revealed.

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