r-process: site, frequency, variability

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About half of all nuclei above the iron group originate in the rapid neutron capture process, r-process for short. Two groups of questions must be answered to gain a thorough understanding of the r-process. One deals essentially with nuclear structure and is needed to describe the abundance distribution. These problems include masses, decay and reaction rates for nuclei far from stability. The other one deals with the astrophysical site of the r-process. We would like to know where the process happens, how often, how much material is created in each event, and how similar or dissimilar are the individual events. Here I focus on the second set of questions. I argue that the core collapse supernovae are the most likely site of the r-process, despite the lack of the quantitative understanding how the required highly neutron rich environment is formed there. The meteoritic data suggest that the frequency of r-process events is the supernova frequency. At the same time, these data suggest that there are at least two kinds of r-process events. This conclusion is supported by the recent observation of the abundance distribution in very metal poor stars. The details of the solar abundance distribution also suggest that neutrino reactions are responsible for some of the nuclei, again supporting the supernova connection. Finally, I show that the observation of gamma decay of the long lived nuclei associated with the r-process would not only prove the supernova origin of the r-process but, more importantly, is essentially within reach of the existing detectors.

Keywords: r-process; core collapse supernovae; frequency

1. Introduction

Approximately half of the heavy elements with mass number \( A > 70 \) and all of the actinides in the solar system are believed to be produced in the r-process. The fundamental r-process theory of Burbidge et al. [1] and Cameron [2] successfully explains the gross features of the solar r-process abundance distribution, such as the existence of abundance peaks at \( A \sim 80, 130, \) and 195. On the other hand, it remains to be established where the r-process occurs and especially how many different kinds of r-process events contributed to the solar r-process abundances.

With the recent progress in both observation and theory, there is a growing consensus that Type II supernovae are the most probable r-process site. It is believed that the r-process occurs in the neutrino-heated ejecta from the hot protoneutron star produced in a Type II supernova [3]. While this so-called “hot bubble” r-process model has some deficiencies, especially the need for very high entropies which might be hard to obtain, but it is attractive for several reasons. Some of them will be discussed below.

The distinguishing feature of such model of the r-process is the intense neutrino flux, which can have important effects on the nucleosynthesis. In particular, the typical neutrino fluences through the ejecta may lead to identifiable signatures in the r-process abundance pattern, thus providing a way to reveal the conditions at the r-process site. Next section, based on the results described in Refs. 4 and 5, describes the postprocessing effects of the neutrino flux.

Regardless of the astrophysical site, two things are needed for an r-process to work: the neutrons and the seed nuclei to capture them. If one always starts from more or less the
same seed nuclei, different neutron-to-seed ratios are required to produce the entire solar r-process nuclear abundance distribution. One can then ask whether different r-process nuclei are made in completely different astrophysical environments (e.g., Type II supernovae vs. neutron star coalescence) or in similar environments but just with different neutron-to-seed ratios. The simplest scenario would be that all r-process nuclei are produced in a unique kind of r-process events with a generic abundance pattern. In that case, the solar r-process abundance distribution merely reflects the distribution of neutron-to-seed ratios characteristic of these unique r-process events.

However, Wasserburg, Busso, and Gallino [6] pointed out that the above minimal approach to account for the solar r-process abundance distribution is not consistent with the meteoritic abundance ratios $^{129}$I/$^{127}$I and $^{182}$Hf/$^{180}$Hf in the early solar system. These authors showed that the r-process events contributing to $^{182}$Hf were fully consistent with the uniform production of the long lived actinides up until the time when the solar system was formed. However, such a rather uniform production would grossly overproduce $^{129}$I (by a factor of ~ 50) and $^{197}$Pd (by a factor of ~ 30). Consequently, they argued that there should be diverse sources for the r-process, one of which produced the r-process nuclei above $A \sim 140$ and another producing those at lower $A$ with a smaller frequency.

In order to account for the solar r-process abundance distribution and to accommodate the meteoritic data on $^{129}$I and $^{182}$Hf at the same time, we consider in Sec. III, following [7], a minimal scenario where two kinds of r-process events contribute to the solar r-process abundances near and above $A \sim 130$.

Finally in the last section we discuss how detection of gamma-ray emission from the decay of r-process nuclei may answer the following questions: (1) Are supernovae a site of the r-process? (2) Are the r-process nuclei produced in relative proportions specified by the solar r-process abundance pattern in supernova r-process events?

Gamma-ray emission characteristic of a radioactive nucleus from an astrophysical event would provide direct evidence for production of this nucleus in this event. In our work [8] we generalize the approach of Meyer and Howard [9] with particular consideration of future gamma-ray detectors. We find that if supernovae are the site of the r-process, a number of r-process nuclei can provide gamma-ray fluxes of $\sim 10^{-7}$ $\gamma$ cm$^{-2}$s$^{-1}$ from a future Galactic supernova at a distance of 10 kpc. In addition, we show that the decay of $^{126}$Sn in the Vela supernova remnant can produce fluxes of a similar magnitude. Detection of such fluxes would be possible for a gamma-ray detector with a sensitivity similar to $\gamma$-ray detectors. We find that such an instrument would be able to detect the diffuse gamma-ray emission from the decay of $^{126}$Sn produced by past supernovae in the Galaxy. Both the detection of gamma-ray emission from the decay of several r-process nuclei (e.g., $^{125}$Sb and $^{194}$Os) produced in future Galactic supernovae and the detection of emission from the decay of $^{126}$Sn in the Vela supernova remnant would prove that supernovae are a site of the r-process, thus answering the first question posed above. In addition, the former detection would allow us to determine whether or not the r-process nuclei are produced in relative proportions specified by the solar r-process abundance pattern in supernova r-process events, thus answering the second question.

Intriguingly, a new supernova remnant (RX J0852.0-4622/GRO J0852-4642) near Vela was discovered recently via its X-ray emission and gamma rays from $^{44}$Ti decay. Its distance is estimated to be ~ 200 pc and an age of ~ 700 yr. We find [10] that this remnant could provide gamma-ray fluxes of $\sim 10^{-7}$ $\gamma$ cm$^{-2}$s$^{-1}$ from the decay of a number of actinide nuclei, thus potentially providing the most direct evidence that the core collapse supernovae are indeed the site of the r-process.

### 2. Neutrino postprocessing

Neutrino reactions can affect the r-process in two ways, by altering the path or pace of the nuclear flow during the synthesis, or by modifying (postprocessing) the abundance pattern after freeze-out (i.e., when all neutrons have been used up). To see what neutrino do, we evaluate the rate of neutrino reactions at radius $r$ from the center of the neutron star.

$$\lambda_\nu \approx 4.97 \left[ \frac{L_\nu(t)}{10^{34} \text{erg s}^{-1}} \right] \left[ \frac{E_\nu}{(100 \text{ km})^2} \right]^2 \times \left( \frac{\sigma_\nu}{10^{-44} \text{ cm}^2} \right) \text{s}^{-1}, \quad (1)$$

where $L_\nu(t)$ and $E_\nu$ are the luminosity and average energy, respectively, of the neutrino species responsible for the reaction, and $\langle \sigma_\nu \rangle$ is the corresponding cross section averaged over the neutrino spectrum (taken to be a Fermi-Dirac distribution). The important reactions in Eq. (1) are the charged-current ($\nu_e, e^-$) reaction and the neutral-current heavy-flavor ($\nu, v^\prime$) reaction: charged-current $\nu_e$ reactions are Pauli blocked for the very neutron-rich heavy nuclei in the r-process, while the lower average energies of $\nu_e$ and $\bar{\nu}_e$ lead to smaller neutral-current cross sections. The evaluation of these cross sections is described in much more detail in Ref. 5.

The charged-current and forbidden neutral-current reactions typically produce a nucleus excited well into the continuum. The nucleus then emits one or more neutrons. This is the process that alters the r-process abundance distribution. The average number of spallation neutrons, $\langle n \rangle$, is obtained by folding the neutrino-induced excitation spectrum with the neutron-evaporation described by the statistical model.

The r-process freezes out when the neutron number density drops below a critical level. The resulting r-process progenitor nuclei would, in the absence of neutrino postprocessing, decay back to the valley of $\beta$-stability, producing the abundance pattern found in nature. However, neutrino postprocessing will modify the final r-process abundance dis-
distribution in a characteristic way. With reasonable assumptions [4, 5] this modification will depend only on the dimensionless parameter $\mathcal{F}$, the neutrino fluence in units of $10^{17}$ erg km$^{-2}$. (Typical expected value of $\mathcal{F}$ is $\sim 0.01$.)

The calculations involve rather straight-forward combinatorics which allows us to evaluate for each $\mathcal{F}$ the probability $P_n$ that $n$ neutrons will be emitted after freeze-out in the $A \sim 195$ and 130 regions. The simplest of these probabilities would be to include them in a standard r-process network calculation. However, alternatively, one can begin with the r-process abundance distribution observed in nature and, for a given neutrino fluence, invert this distribution to determine the initial distribution that must have existed prior to the neutrino postprocessing. Independent of the exact value of the neutrino fluence, the most important result of the inversion described above is the discovery that 8 nuclei, lying in the windows $A = 124 - 126$ and $183 - 187$, are unusually sensitive to the neutrino postprocessing. These nuclei sit in the valleys immediately below the abundance peaks which can be readily filled by spallation off the abundant isotopes in the peaks.

This observation allows us to place firm upper bounds on the fluence $\mathcal{F}$ (0.031 for $A \sim 195$ and 0.045 for $A \sim 130$) characterizing the freeze-out of the abundance peaks. Moreover, with just the parameter $\mathcal{F}$ at our disposal we can explain the observed abundances of the nuclei in the windows $A = 124 - 126$ (for $\mathcal{F} = 0.031$) and $183 - 187$ (for $\mathcal{F} = 0.015$). It is remarkable that the eight isotopes we initially identified as having great sensitivity to neutrino postprocessing prove to have abundances fully consistent with neutrino-induced synthesis during postprocessing. We consider this as strong evidence suggesting that the r-process does occur in an intense neutrino fluence, and thus that the interior region of a Type II supernova is the site of the r-process.

3. Diverse sources for the r-process

As pointed out in the Introduction, Wasserburg, Busso, and Gallino [6] showed that the meteoritic abundance ratios $^{129}$I/$^{127}$I and $^{182}$Hf/$^{180}$Hf in the early solar system imply that there should be diverse sources for the r-process. In order to account for the solar r-process abundance distribution and to accommodate the meteoritic data on $^{129}$I and $^{182}$Hf at the same time, we considered in Ref. 7 a minimal scenario where two kinds of r-process events contribute to the solar r-process abundances near and above $A \sim 130$. Using simplified r-process calculations and taking into account other constraints on the r-process site, we showed that the main features of the solar r-process abundance distribution from the peak at $A \sim 130$ up to the region of the actinides can be reproduced by a reasonable superposition of these two kinds of r-process events.

Specifically, the first kind of events (case H, “H” stands for mainly producing the higher-mass r-process nuclei) are mainly responsible for the r-process nuclei near and above $A \sim 195$. They also make a significant amount of the nuclei between $A \sim 130$ and 195, including $^{182}$Hf, but very little $^{129}$I. The r-process nuclei near $A \sim 130$ are made in the second kind of events (case L, “L” stands for mainly producing the lower-mass r-process nuclei). Furthermore, the meteoritic data on $^{129}$I and $^{182}$Hf allow us to associate the events in case H with the most common Type II supernovae (Coincidentally, “H” also stands for occurring with a high frequency) and those in case L with the much rarer ones which occur $\sim 10$ times less frequently (“L” also stands for occurring with a low frequency). In order to match the solar r-process abundance pattern, the rarer events in case L must eject $\sim 10$–20 times more r-process material in each event.

In the calculation we follow the time development of the abundances of individual nuclei, $Y(Z, t)$ by solving the corresponding set of differential equations. We assume that the $(n, \gamma) \rightarrow (\gamma, n)$ equilibrium is maintained, and further assume that all seed nuclei have charge $Z_s = 34$ and mass number $A_s = 90$ typically found for the products of the $\alpha$-process. We start with only neutrons and seed nuclei, and thus at freeze-out

$$\bar{A}(t_{\text{FO}}) \approx A_s + \frac{n}{s},$$

where $n/s = Y_n(0)/Y(Z_s, 0)$ is the neutron-to-seed ratio. This is the only free parameter for each of the two cases. It turns out that this simplified model suggests that the case H can be characterized by $n/s = 92$ and requires about 0.86 s till freeze-out. For the case L we get $n/s = 48$ and duration of 0.44 s.

But the important point is that the meteoritic evidence suggests that new material from the case H was injected into the protosolar nebula within $10^7$ years prior to the solar system formation. We can relate this to the frequency of supernovae in the galaxy. For an explosion energy of $\sim 10^{51}$ erg, typical for a SN II, the initial velocity of the supernova ejecta is $v_0 \sim 10^3$ km s$^{-1}$. In about a few $10^3$ yr, the supernova sweeps over a distance of about 6 pc and mixes with the same amount of the interstellar medium as the total mass $M_{\text{ej}}$ of the original ejecta. At times $t_{\text{exp}} \gg 10^3$ yr, the expansion (commonly known as “snow plowing”) under momentum conservation reaches the radius $R$

$$R \approx \left(\frac{3 M_{\text{ej}}v_0 t_{\text{exp}}}{\rho_{\text{ISM}}\pi}\right)^{1/4},$$

where $\rho_{\text{ISM}}$ is the density of the interstellar medium. Thus, $R \approx 70$ pc in $t_{\text{exp}} \sim 10^4$ yr. Interestingly, within the lifetime of $^{182}$Hf, the number of supernovae in a region of $\sim 70$ pc in size is about one assuming a total Galactic volume of $\sim 700$ kpc$^3$ and a supernova frequency of $\sim (30 \text{ yr})^{-1}$ in the whole Galaxy. Therefore, the meteoritic data suggest that the r-process events in case H occur with a frequency of $f_{\text{SN}} \sim (30 \text{ yr})^{-1}$ in the whole Galaxy, as also argued by Wasserburg et al. [6]. That agreement strongly supports the assumption that supernovae are the site of the r-process, at least for the case H.
4. Implications for $\gamma$ ray astronomy

In this section we assume that supernovae are the site of the r-process. Gamma-ray emission from the decay of nuclei produced in a supernova may be detected only after it becomes transparent to gamma rays, which typically takes several years. Consequently, r-process nuclei that may be of interest to gamma-ray astronomy must have lifetimes of $\sim 1$ yr or longer. A search through the Table of Isotopes identifies seven such nuclei. The five relatively short-lived ones are $^{125}$Sb, $^{137}$Cs, $^{144}$Ce, $^{155}$Eu, and $^{194}$Os, and the two long-lived ones are $^{126}$Sn and $^{182}$Hf. We emphasize that all of these nuclei are bypassed by the s-process, and are made only in the r-process.

Assuming that the solar r-process composition represents the Galactic average, we can estimate the average amount of mass in a radioactive r-process nucleus produced in a supernova as

$$\delta M \approx \frac{X_{\odot}^5 M_G}{f_{SN} M_G},$$

where $X_{\odot}^5$ is the solar r-process mass fraction of the stable decay product of this nucleus (e.g., for $^{125}$Sb, $X_{\odot}^5$ is from $^{126}$Te), $M_G$ and $t_G$ are the total mass and the age of the Galaxy, respectively, and $f_{SN}$ is the frequency within the Galaxy for the supernovae which produce this nucleus.

We can then readily calculate the gamma-ray flux to be detected from its decay as (we neglect the delay between production and onset of gamma-ray transparency)

$$F_\gamma = \frac{N_A \delta M I_\gamma}{4\pi d^2} \frac{A}{\bar{v}},$$

where $d$ is the distance to the supernova, $N_A$ is Avogadro’s number, $A$ is the mass number of this nucleus, $\bar{v}$ is its lifetime, and $I_\gamma$ is the number of photons emitted at a specific energy $E_\gamma$ per decay of this nucleus. The expected gamma-ray fluxes from the decay of the five relatively short-lived r-process nuclei are given in Table I of Ref. 8 for a supernova at a distance of 10 kpc. The typical values are $\sim 10^{-7} \, \text{cm}^{-2} \, \text{s}^{-1}$, perhaps reachable in the next generation of the planned $\gamma$ ray detectors.

The long-lived nucleus $^{126}$Sn ($\bar{v} = 1.44 \times 10^{10} \, \text{yr}$) can be detected only from a nearby supernova. The corresponding flux for the reference value of $d = 200 \, \text{pc}$ is

$$F_\gamma \approx 2.2 \times 10^{-7} I_\gamma \left( \frac{\delta M}{5 \times 10^{-7} \, M_\odot} \right) \times \left( \frac{200 \, \text{pc}}{d} \right)^2 \gamma \, \text{cm}^{-2} \, \text{s}^{-1}. $$

Interestingly, the distance to the Vela pulsar is estimated to be only about 125–500 pc. Furthermore, its age is estimated to be about 10$^4$ yr, much less than the lifetime of $^{126}$Sn. So if the supernova associated with the Vela pulsar produced $^{126}$Sn, then most of the radioactive $^{126}$Sn nuclei initially produced in the supernova will remain there for a very long time.

A future Galactic supernova will announce itself by a powerful neutrino burst even if its optical display is obscured from us. The delay between the explosion and onset of gamma-ray transparency leaves time for directing suitable detectors to search for gamma-ray emission from the decay of the r-process nuclei mentioned earlier. If gamma-ray emission from the decay of these r-process nuclei were detected from the supernova, this would prove that these nuclei are produced in supernovae.

In addition, we are interested in determining whether or not these nuclei are produced in relative proportions specified by the solar r-process abundance pattern in supernova r-process events. If the relative production of these nuclei were indeed specified by the solar r-process abundance pattern, the corrected fluxes would be proportional to $(X_{\odot}^5/A)(I_\gamma/\bar{v})$. The distance to the supernova is not needed for establishing this proportionality. However, some of these nuclei, $^{125}$Sb, $^{137}$Cs, $^{144}$Ce, and perhaps $^{155}$Eu, belong to the infrequent case I, described earlier, while $^{194}$Os belongs clearly to the case H. Thus, the relative intensities of these radioactive sources could test that hypothesis. Detection of gamma-ray emission from the decay of $^{126}$Sn in the Vela supernova remnant would prove that the r-process nuclei near $A \sim 126$ are produced in supernovae. If that supernova belonged to the case L, the corresponding $\gamma$ flux would be correspondingly higher, and readily observable.

Intriguingly, a new supernova remnant (RX J0852.0-4622/GRO J10501-4642) near Vela was discovered recently via its X-ray emission and gamma rays from $^{44}$Ti decay. As $^{44}$Ti has a lifetime of $\sim 90$ yr, the detection of the corresponding decay gamma rays clearly establishes this remnant as a young object with an estimated age of $\sim 700$ yr. Its distance is estimated to be $\sim 200$ pc. These parameters are consistent with X-ray and gamma-ray observations leading to the discovery and are adopted for our discussion here. In the following discussion, we assume that it was produced by a core-collapse supernova (see Ref. 10 and references therein).

With a distance of $\sim 200$ pc and an age of $\sim 700$ yr for the new supernova remnant, we find that this remnant could provide gamma-ray fluxes of $\sim 10^{-7} \, \gamma \, \text{cm}^{-2} \, \text{s}^{-1}$ from the decay of $^{226}$Ra, $^{229}$Th, $^{241}$Am, $^{243}$Am, $^{249}$Cf, and $^{251}$Cf with lifetimes of $\sim 500$–$10^4$ yr.

The key quantity for estimating the flux $F_{\gamma,i}$ is $(\delta M)_i$, the amount of a radioactive nucleus “i” produced in the supernova associated with the new remnant. We first calculate the average amounts $(\delta M)_i$ of the relevant nuclei produced in a supernova using the solar abundances of the actinides. We assume that the production of such nuclei by past Galactic supernovae occurred at a uniform rate before solar system formation. Each of these nuclei are produced by a chain of direct $\beta$-decays after r-process freeze-out and by $\alpha$- and $\beta$-decays of progenitors from other chains.

We find that the calculated average amount of production per progenitor for $^{232}$Th, $^{235}$U, and $^{238}$U, is $(\delta M)/N_{\text{pro}} \approx 2 \times 10^{-8} \, M_\odot$. The value $(\delta M)/N_{\text{pro}} \approx 0.7 \times 10^{-8} \, M_\odot$.
for $^{244}$Pu is somewhat lower. To check how well $(\delta M)_i$ represents the actual amount of production $(\delta M)_i$ in a specific supernova, we use the observed Th abundances in very metal-poor stars in the Galactic halo [11], and find a remarkable agreement. This makes it possible to calculate with reasonable confidence the expected $\gamma$-ray fluxes from the newly discovered supernova remnant (see Table I of Ref. 10). Again, the characteristic magnitude of several lines is $\sim 10^{-7} \, \gamma \text{ cm}^{-2} \text{s}^{-1}$.

Detection of gamma-ray fluxes due to the decay of nuclei with $A > 209$ from a supernova or a supernova remnant would be the best proof for a supernova r-process site as these nuclei are produced solely by the r-process. Further, such a detection provides the most direct information on yields of progenitor nuclei with $A > 209$ at r-process freeze-out, which can offer valuable guidance for theoretical studies. Finally, such a detection also provides a direct means of comparing the r-process yields in a single supernova event with the solar r-process abundance pattern.

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