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Open Access Journal of Astronomy
ISSN: 2996-6701

Cosmic Baby and the r-process Nucleosynthesis

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Review Article
Volume 2 Issue 1
Received Date: March 30, 2024
Published Date: April 22, 2024
DOI: 10.23880/oaja-16000110

Abstract

Astrophysical origin of the rapid neutron capture process (i.e., r-process) remains a mystery. Among the known r-process sites radio-actively powered kilonova, produced by binary neutron star mergers, attracted the astronomers a promising source in the light of gravitational wave radiation. The first detected binary neutron star merger event GW170817 confirmed the existence of binary neutron star (BNS) in nature while its associated properties such as transient electro-magnetic emission in the form of x-rays, long and short gamma ray bursts (l, s GRBs), First Radio Bursts (FRBs) offer the astronomer to rethink about the origin of the r-process abundances in the light of Magnetars, created in both supernova explosion and also in neutron star merger, as a r-process contributor.

Recently detected Cosmic Baby i.e. Swift J1818.0 – 1607 is a young magnetar of 240 years aged with super-strong magnetic fields ~ 8.9424 x 10^{17} G and ellipticity ~ 9 x 10^{-3}. Due to its youngness among the 31 detected magnetars till today, it may provide x-ray lines emitted by the r-process abundances which makes it as an important promising source in the eyes of LOFT, NuSTAR detectors.

This author proposes that this cosmic baby can be considered as a suitable astrophysical source decoding of its observed results may unravel the realistic situations of the magnetar at the time of merger, supernova explosion, etc. for generation of super heavy elements like Eu, Ti.

Keywords: Gravitational Wave; Binary Neutron Stars; Magnetars; r-Process

Abbreviations: BNS: Binary Neutron Star; FRBs: First Radio Bursts; AGB: Asymptotic Giant Branch; GRBs: Gamma Ray Bursts; CCSN: Core Collapse Supernova; ISM: Interstellar Medium; WPA: Waiting Point Approximation; BAT: Burst Alert Telescope.

Introduction

Neutron capture nucleosynthesis [1-5] is the main responsible for the production of elements heavier than iron (Fe) although the heavier elements up to the Actinides still remains uncleared area in stellar nucleosynthesis as well as in nuclear physics. This process can be divided mainly into two: slow capture (s-process) and rapid capture (r-process) according to the comparison study between the neutron capture reaction (n, γ) rates of the involved nuclei and their half-lives [6], series of subsequent neutron capture (separated by β-decays). As the s-process nucleosynthesis follows a path along the valley of β-stability which is close to the strongly bound isotopes of a given atomic weight (or mass number) "A", our knowledge of s-process nucleosynthesis is far more than that of r-process nucleosynthesis. For example,

- the main site of the slow neutron capture is the final Asymptotic Giant Branch (AGB) phase of the low- and intermediate mass stars;
- the stars with mass up to 3 $M_\odot$ are responsible for the production of the main neutron source $^{13}C\ (\alpha,n)^{16}O$ reaction with the conditions-typical operating energy ~ 8kev and neutron density ~ $10^6 - 10^7\ n/cm^3$ [7];
- the second important neutron source in this AGB phase is $^{22}Ne\ (\alpha,n)\ ^{25}Mg$ reaction which is active when ^{22}Ne burns effectively at temperature $(3 - 3.2) \times 10^8$ K [8];
- the neutron poison reactions which significantly constrain the s-process efficiency in this phase are $^{12}C(n, \gamma)^{13}C$, $^{16}O\ (n, \gamma)\ ^{13}C$, $^{16}O(n, \gamma)\ ^{17}O$, $^{17}O(n, \alpha)\ ^{14}C$, $^{14}N\ (n, p)^{14}C$ [9].

In brief, for the question "why s-process is considered as a well-known nucleosynthesis mechanism" it can be said that because of its main component occurs in common astrophysical objects as well as its neutron capture reactions are not hampered by the coulomb barrier [10].

Regarding r-process, various observations suggest that the r-process is believed to occur in such an environment having quite large neutron fluxed (i.e., $n_n > 10^{20}\ cm^{-3}$) i.e. during the late evolutionary stages of massive stars (single or binary). For example, magneto-rotational supernovae [11], neutron star mergers [12], collapsars (i.e. a star which has undergone gravitational collapse) [13]. But the main problem is the exact location / sites where the r-process occurs that still remains a matter of debate.

Why r-Process and its Importance

More than 70 years have passed the astrophysical origin of the rapid neutron capture process i.e., r-process still remains a mystery [14]. Our present knowledge of r-process suggests that violent events are the seed of the r-process abundances which are associated with the nuclear physics uncertainties. For example, recent discovery of the radioactively powered kilonova (produced due to violent deaths of neutron stars) emission is the most important site of the r-process in the universe [11] in addition with our two known viable sites (a) core collapse supernovae which are "explosions" at the end stages of massive star evolutions and (b) compact object mergers which are violent collisions of stellar remnants arises due to binary compact object mergers (Figure 1). This means that the interplay between the r-process and the dynamics (such as tidal ejecta, tidal deformation) of compact object merger (such as binary neutron stars: NS – NS; blackhole – neutron star BH-NS or binary black holes BH – BH) which may be accompanied by electromagnetic counterparts or gamma ray bursts (GRBs) provide the astronomers as probes of understanding the secret of the r-process through the detection of gravitational wave radiation.

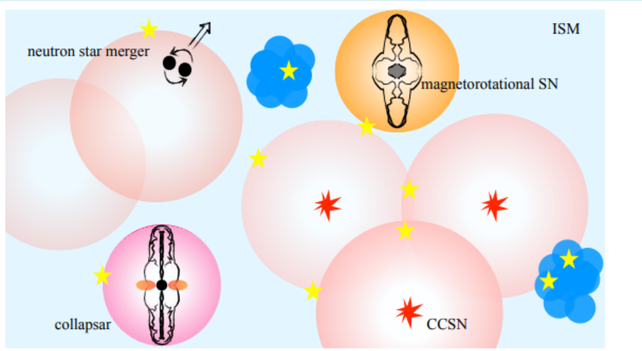

Figure 1: Four potential sources of r-process are shown. Out of these only two sources i.e. core collapse supernova (CCSN) and neutron star merger offer kick velocity and ejecta (blue colour) into interstellar medium (ISM) [15].

Recent Observational Evidence for r-Process Nucleosynthesis

Short duration GRB and Macronova: Till date various observational parameters, obtained from the analysis of solar r-process abundances [16,17], suggest that

- the robust r-process environment produces heavy r-processed elements (i.e., $A \geq 130$) [17];
- Environment of old metal-poor halo stars are capable to produce a wide variety of r-abundances including r-elements like Europium ('Eu') [18] with an indication of a different weaker neutron capture source;
- Observation of Thorium ("Th") in low metallicity stars [19], etc.

This means that above mentioned variation in observed r-elements are may be due to the different production sites. In other words, there is a variation in the r-process strength for the same r-process sites.

If we look into the neutron star mergers, then these events are identified through the detection of GRBs or micronova [20] via the light curves and spectra of their electromagnetic counterparts. Studies of the GRB130603B (accompanied with micronova) [21-23] indicates that

- Mass can be ejected in this event.
- Late-time micronova light curves can be significantly affected by the α-decay generated from the trans-Pb isotopes. This means that sufficient amount of short-duration GRB can be produced by these heavy elements.
- This creates a problem in determining the actual abundance pattern i.e., identifying the specific features produced by a particular heavy element because of mixing/overlapping that of produced by other many

elements including radio-active elements [20,24].

Measurement of Radio-active isotopes addition in deep sea sediment: Radio isotope ^{60}Fe has half-life of 2.6 x 10^6 years. So, if this ^{60}Fe is produced in the event of explosions of massive stars several million years ago then due to its evolution this isotope can be found in deep sea sediments as stellar debris. In particular, if such an explosion occurred at a nearby distance approximately two million years ago [25,26]. Another isotope ^{244}Pu (Plutonium) has a half-life ~ 8.1 x 10^7 years and also associated with the supernova explosion. Thus, if one assume that the strong r-process took place in any supernova explosion with the release of r-process matter amounting approximately 10^{-4} to 10^{-5} $M_\odot$ then this would explain the present day observed solar abundances. But recent detection of ^{244}Pu [27] indicates that

- The detected amount is lower by two orders of magnitude than the expected as per prediction.
- The Actinide nucleosynthesis is very rare.
- Supernova explosion did not contribute significantly for enriching r-process matter in solar abundance.
- In order to explain the origin of strong r-process matter as presently measured in solar system suggests the evidence of a new but rare event of r-process origin other than the binary neutron stars merger [28]. If so, in that case this would explain the low levels of deposited ^{244}Pu isotopes recently observed in deep-sea-sediments [28].

r-Process in Neutron Stars Mergers

Simulation Data: Prior the detection of first binary neutron star merger event GW170817 (as detected on 17th August 2017) theoretical works and hydrodynamical simulation studies suggest that when two neutron stars collide or merge [29-32] then

- a small fraction of mass is ejected and if this ejecta is sufficiently neutron rich, then within seconds it will converted into heavy elements through rapid neutron captures (i.e. r-process) [33];
- the subsequent radio-active decay (i.e., β-decay) of these nuclei will heat these nuclei (i.e., ejecta) for days that can power transient electromagnetic emission which will be significantly dimmer than the ordinary supernova. If so, then identification of such events will offer a new kind source on the origin of r-process nuclei [34] (Figure 2)

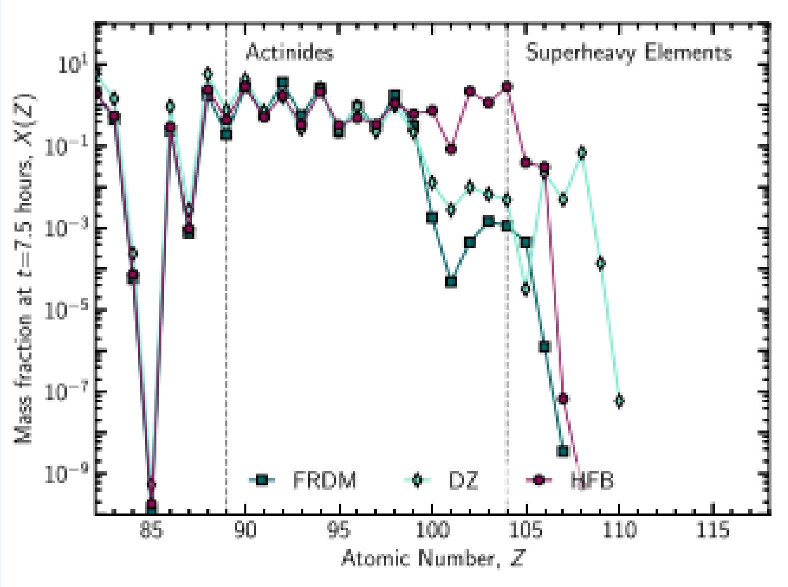

Figure 2: Mass fraction yields of the heaviest elements at 7.5 hr post-merger for three nuclear mass model and fission barrier combinations. Note that under the same astrophysical conditions, there can be over 3 orders of magnitude difference in the mass fractions of superheavy elements that are synthesized as per different adopted models. FRDM — Finite Range Droplet Model; DZ —Fission barrier based model of Duflo & Zuker, and HFB —Hartree-Fock-Bogoliubov model (adopted from [69]).

Observational Data: The first binary neutron star merger event GW170817 was detected on 17th August 2017 and analysis of its observational data shows that

- the gravitational wave GW170817 event is compatible with a binary neutron star inspiral event.
- During merger a mass ~ 10^{-4} – 10^{-2} $M_\odot$ of neutron-rich material is ejected during dynamical time scale [35,36].
- Mass ejecta from this binary merger is the main astrophysical site for the heavy element production via r-process [37].

- As an observational imprint of r-process heavy element production the kilonova electromagnetic transient was observed in the counterpart of GW170817 [38].
- Analysis of the kilonova counterpart of GW170817 (i.e. observation of both blue and red counterparts) suggests that the ejecta had a broad range of compositions in which at least a fraction being free of lanthanides [39,40].
- Velocity of the ejecta is 0.27c which suggests that a long-lived remnant could be excluded [39].

In brief, it can be said that the best fit of the radioactively powered kilonova AT20gfo light curves [41] (associated with the short duration gamma ray burst GRB170817A) of the gravitational wave eventGW170817 provided a direct evidence which supports that binary neutron star merger as a crucial astrophysical sites for the synthesis of heavy element beyond iron via r-process nucleosynthesis (Figure 3).

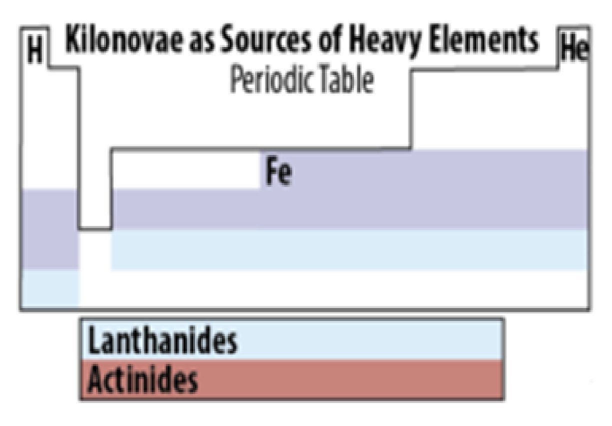

Figure 3: Schematic diagram showing the heavy elements created in binary neutron star merger, in particular contribution of kilonova. Colour representation of wavelength as probe production of concerned element [42].

- violet representing UV and near-UV,
- light blue representing optical and some NIR, and
- red showing NIR and IR (adopted from [48]).

Necessity of a Massive Single Star as r-Process Contributor

In the previous section it is discussed that compact binary mergers contribute towards reproduction of heavier solar r-process abundances that can explain short duration GRBs and also its related phenomena like macronova events. In the case of binary neutron star system initially two prior supernova events (for producing two neutron stars) and gravitational wave radiation driven in-spiral for merger are essential.

Secondly, the time delay between the Fe- producing supernova and ejection of r-process materials that can shift the appearance of a typical r-process tracer, like Eu, to higher metallicities (Fe/H) [43,44] depending on coalescence time, mixing of ejecta in the surrounding ISM, etc. In this context, it is to be noted that strong magnetic field and fast rotation might play a significant role. For example, core collapse supernovae which leaves behind a neutron star with strong magnetic field ~ 10^{15} G, (so called Magnetar), show similar characteristics in the amount of r-process ejecta as that of in the case of neutron star merger [45,46]. Note that neutron stars are the end result of massive single star's evolution so they do not experience any delay which is applicable in the case of binary evolution [47].

A simulation study of galactic evolution shows that the superposition of MHD-jet supernovae (magnetar) and neutron star merger has matched with the observations over the whole galactic evolution for the considered metallicities ranging from the lowest to the present updated values. Inspite of existing uncertainties in the mixing processes, star formation rates that affect the behavior at the lowest metallicities. Not only that, another significant result is the prediction of a robust and unchangeable r-process abundance pattern arises from neutron star merger process, though the known fact is that the strength of the r-process, in general, varies depending on rotation frequency, strength of magnetic field and neutrino heating.

Therefore, keeping in view the existed observational result of 'Eu / U' (which indicates the production of actinides robustly coupled to 'Eu") at low metallicities which shows a variation of a regular r-process pattern in several events indicating a changing amount of actinides at metallicities around [Fe/H] = -3 [19,48]. This means that such variation in r-process pattern are not expected from compact binary merger event and this might indicate the possibility of another new source other than the known binary neutron star merger. In other words, the new source possibly arise due to an effect of MHD-jet supernova (i.e. Magnetar) at low metallicities. The reason being is that

- the MHD-jet supernovae are more frequent in comparison to that in the present galaxy;
- at low metallicities, stars have less wind and mass loss as well as less angular momentum loss resulting which it turns into a more promising source that satisfies these initial conditions at the onset of collapse.

Effect of Magnetic Field on r-Process

In the above we see that the merging of neutron stars offers important results:

- The r-process nuclides can be formed in the merger event;
- This event is capable to produce 100 times more nuclides in comparison to that of produce during core collapse supernova (CCSN) explosion process.
- At temperature $T \leq 3 \times 10^9$ K the actual r-process begins and then all other nuclear reactions occur following it.

Studies of the Waiting Point Approximation (WPA) [49] provide another significant result suggesting that only beta decays have a connection between isotopic chains at a temperature of about 3×10^9 K. As the time period for neutron capture processes in the environment of large neutron densities is much shorter compared to the β-decay as well as capability of producing nuclei with a neutron separation energy of ≤ 2 MeV, this r-process proceeds close to neutron drip line. As a result, the photo-break up reaction (γ, n) can remain very active at temperature of about 10^9 K and ultimately, nuclear statistical equilibrium (NSE) can be established between neutron capture and photo-breakup.

Further studies by considering neutron capture cross section, abundance distribution in each isotopic chain (i.e. ratio of two neighboring isotopes), neutron separation energy, indicate some significant results:

- Neutron separation energy shows its dependency on nuclear masses by imposing conditions of r-process: number of neutrons $n_n \sim 10^{20}$ cm^{-3}, temperature $T \sim 10^9$ K at time scale ≤ 1 s [49].
- As the nuclei closer to the stability region have a longer β-decay period, the rate along the r-process nuclei is determined by β-decay.
- The strong magnetic field plays a leading role towards the increasing neutron gamma capture reaction cross section [50] i.e. the effective r-process scenario enhances at high magnetic induction.
- R-process path having magnetized nuclei means longer neutron separation energies.
- Due to the magnetic effect r-process shifts towards the nuclides with smaller masses.
- High magnetic induction effect on 44Ti and 48Ti isotopes makes an opportunity to observe directly 44Ti isotopes in earth-based environment.

Cosmic Baby, Magnetar Formation at Low Metallicity

Magnetar at Low Metallicity: It is believed that magnetars are born within in core collapse event with high angular momentum progenitors or in the aftermath of binary neutron star merger event. In the case of core collapse, at birth time magnetars are expected to have [50]

- spin periods $P_o \sim 1 - 3.2$ ms with median value of 1.6 ms
- corresponding rotational energy $E_{rot} \approx 2 \times 10^{52}$ ergs $(Po/1ms)^{-2}$
- spin down time scale $t_{sd} \approx 1.5 \times 10^4$ s $(B/10^{14}\ G)^{-2}\ (Po/1\ ms)^2$

Where B = surface dipole magnetic and t = age of the magnetar.

On the other hand the merger of binary neutron stars leads to the formation of another compact object whose final nature or ultimate outcome depends on the various factors such as remnant's mass, its ability to support itself against its own gravity, spin down, cooling off. For example, in the case of binary neutron star merger event GW170817 the component masses, inferred from the observational data, show that it lies

a. Between 1.00 $M_\odot$ and 1.89 $M_\odot$ when large spins are taking into account, and
b. Between 1.16 $M_\odot$ and 1.60 $M_\odot$ under restricted spins

as well as total mass = $2.73^{+0.04}_{-0.01}\ M_\odot$ [51]. The survival of final remnant thus gives different strategically situations:

- if it is more massive then remnant immediately collapse into black hole (BH);
- if it is less massive then remnant falls in two subdivisions i.e. either unstable hyper massive neutron star (HMNS) or supra-massive neutron star (SMNS) [52,53] and both of which suffer gravitational collapse into a black hole — and stable neutron star [54]. This implies that the ultimate form of the remnant of a binary neutron star merger can be either a black hole or a highly magnetized fast spinning neutron star, so called Magnetar.

Significance is that these events, as per hypothesis, all are related to (a) the origin of short gamma ray bursts (sGRB), (b) the origin of Kilonovae (KN) and (c) formation of heavy elements through r-process [55-57].

Regarding ultra-strong, fast spinning supra-massive neutron star Parui RK, et al. [58-60] suggested that such neutron star can be considered as triaxial star (for example, Cosmic Baby). This means that due to fast spinning and ultra-strong magnetic field a magnetar (i.e. neutron star) suffers deformation, a change in its ellipticity in shape and turns into triaxial star.

It is to be noted that magnetar like compact object is formed in two ways — one way from the core of a massive progenitor star through supernova explosion, and the other way from the binary neutron star merger. Therefore, various properties of compact object, like magnetar, observed during pre-, at the moment, and post – formation phases of magnetar through core collapse supernova can have a link with that of the same phases in the case of magnetar formed from binary neutron merger, etc. In the case of core collapse supernova direct measurement or observation is possible resulting which the collected data have more realistic information in comparison to that of information received from the detection via gravitational wave radiation. This means that results from the observation of magnetar, originated from core collapse supernova, provides a probe to the astronomers in searching the realistic phenomena / physical phases suffered by the Magnetars inside the merger which are never be possible to detect / infer from the observation via gravitational wave radiation.

Cosmic Baby: Magnetars, detected through direct observations, are relatively old (i.e. ≥ 10^3 years). So, information about their birth properties and progenitors are not well understood. The Swift Burst Alert Telescope (BAT) on board the Neil Gehrels Swift Observatory [61] detected a typical characteristic of a short burst originated from a magnetar on 12th March 2020 at 21:16:49 UT [62]. This newly detected uncataloged X-ray source, the Swift J1818.0 – 1607, is presently known as Cosmic Baby. The important parameters of this cosmic baby are:
Characteristic age ~ 240 years [63]
Surface magnetic field ~ 2.7×10^{14} G
Dipole magnetic field Strength at poles ~ 7×10^{14} G
Spin Period ~ 0.7333920 s
Spin Period Derivative ~ 8.2×10^{-11} $s.s^{-1}$ [64]
Period devivative ~ 9×10^{-11} $s.s^{-1}$
Coherent Periodicity of X-ray signal = 1.36 s [65]

Magnetars are isolated neutron stars having strong magnetic field ~ 10^{16} – 10^{17} G or even more. As of today, 30 magnetar have been detected excluding this Swift J1818.0 – 1607. For these 30 magnetars their spin / rotational periods ranges from 2 to 10 s and surface dipole dipole fields are 10^{13} to 10^{15} G [66].

Analysis of the observed data indicates that magnetars are young, most of them having characteristic spin- down ages of less than 104 years [67]. They are slow rotator, therefore, their spin down energy loss cannot power their emission. Since this cosmic baby is the newly born youngest magnetar of 240 years age, i.e. the baby phase in compared to thousands of years. The estimated ellipticity of this cosmic baby i.e. 9×10^{-3} will remain almost at that value for exhibiting a triaxial nature for atleast 700 – 760 years, it can have potentials to study the magnetic effects on various transients properties, r-process abundances, etc. [58-60].

Inarticulate Arreas in Binary Neutron Star Merger that Need Decoded of the Results Obtained from Cosmic Baby Observation

Scattering in r-process abundances w.r.t. Eu at low metallicities provides the origin of it i.e. either the result of inhomogeneous admixture from the rare events or different origin ? Earlier studies of galactic chemical evolution considering variation in abundance pattern arises from neutron star merger events with symmetric / asymmetric neutron star mass suggest that this vartiation may be wither due to a weak r-process with Fe co-production or a strong r-process with "no" or negligible Fe co-production [67-69]. On the other hand, metallicities less than [Fe/H] ≈ -2.5 do not ascertain the imprint of only one nucleosynthesis event rather the possibility of super-position events [70].
It is true from the observational evidences that heavier elements such as Eu (Europium), gold, U (Urenium) etc., are produced via the r-process. Supernova explosion of very first stars in the universe led to (a) the enrichment of their surrounding environments with new materials. But for production of these heavy elements require dense, hot and high neutron rich environment [71]. How such environment appears not yet known clearly.
R-process abundance pattern of the early emission from GW170817 event implies an effect of absorption features on optical spectra. Retrieval of r-process abundance patter from the observed parameters in Kilonova, arised from binary neutron star merger, gives possible exact physical condition i.e. the moment of the ejected matter begins [72].
Transients as Signature of Magnetar Birth: The detection of x-ray decay lines originated from the r-process nuclei associated with young or nearby phased of the magnetar provides a clue when "exactly the birth of a magnetar" takes place and a link between birth period of the magnetar and the "origin of the r-process". In fact, an appreciable abundance of r-process isotopes to be present in the binary merger remnant such that the half-lives of the parent nuclei must be comparable or longer than the age of the binary system. Where as in the case of young magnetar as supernova remnant the decay time must be longer than the time taken by the ejecta for becoming transparent to the x-ray line.
In this context, high r-process yields play an important role. Assuming a total r-process yields of the fiducial r-process abundance (M) in the supernova remnant magnetar scenario Ripley JL, et al. [73] found in their simulation study the value of $M \approx 6 \times 10^{-3} M_{\odot}$. This means event rate is $R \sim 10^{-4}$ yr^{-1} [74]. Now, if the neutron star mergers occur in our Milky Way with this estimated event rate $R \sim 10^{-4}$ yr^{-1} then it means that the event rate is ~ 300 times lower than that of associated with core collapse supernovae. Thus, if the neutron star merger events are the dominant Galactic r-process source, then the r-process mass ejecta per binary neutron star merger (NSM) must be ~ 300 times higher than in the case of magnetar in supernova originated. In other words, higher ejecta mass means potentially larger x-ray signals. But the exact location of the x-ray sources i.e. location of the remnant is unknown. The average r-process yields in Galactic supernova magnetar have an x-ray of 27.3 KeV which is within the detectable range of the detectors LOFT, NuSTAR. We have a hope that survey of galactic plane for r-process line may add new information on the merger location.

Decoding of r-Process Ejecta: After the discovery of binary neutron star event merger GW170817 one of the open questions arose: "Whether neutron star mergers are the only astrophysical sites which are capable of producing r-process elements”? As such type of environment is not available on the earth or not possible to create in realistic sense, thus numerical simulations are the only probe in the hands of the astronomers to get an idea what will be in realistic situation.

Numerical Simulation (1)

A study of numerical simulation showed two important results which are [75]:

- The r-process material amounting (0.01 – 0.1) $M_\odot$ could be produced as an outflow from the accretion disk surrounding the rapidly rotating black hole that form as a remnant in both the cases (a) neutron stars merger as well as (b) collapsar i.e. collapsing massive stars associated with the long duration gamma ray bursts.
- Detection of GW170817 confirmed the hallmark signature of r-process nucleosynthesis in a binary neutron star merger. Thus, one can try to correlate between the rates of and expected yields from neutron stars merger with that of rare core collapse supernovae pointing towards (i) the total amount of r-process production in the Universe and ii) an alternative r-process site.

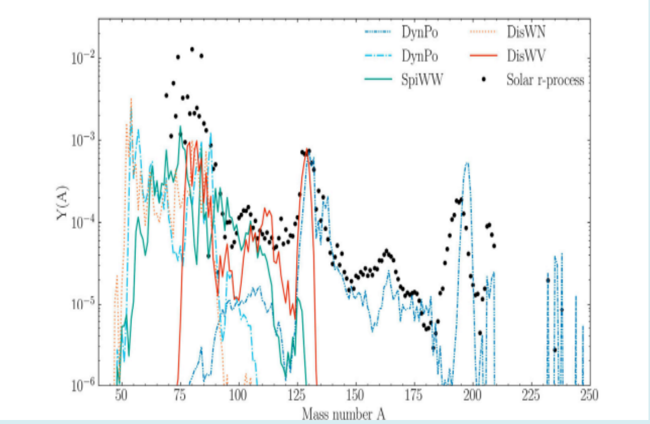

Figure 4: Final abundances Y(A) versus mass number A for the five parameterized trajectories arise during neutron stars merger. Dynamically ejected parameters are denoted as
(i) at equatorial (DynEq) and(ii) at polar (DynPo) angles (blue and cyan lines, respectively), and (iii) winds expelled after the merger due to the propagation of spiral arms in the NS remnant (SpiWW; green line), (iv) neutrino irradiation (DisWN; orange line), and (v) viscous processes (DisWV; red line). Note that for comparison the scaled solar r-residuals, obtained by multiplying the solar system abundances of Lodders K [76] by the r-fractions from Prantzos N, et al. [77] (adopted from [78]).

Numerical Simulation (2)

r-Process ejecta for binary neutron star merger Vs. solar process. In the case of binary compact objects merger the energy is released via the emission of gravitational waves (as energy loss) resulting which the binary orbit gradually shrinks, inspiral of the two compact objects ends with their merger. To understand what will happen at the last phase of the coalescence Vescovi D, et al. [78] performed numerical simulation focusing on the neutron capture rates, and sensitivity for typical outflows from the neutron stars mergers. In their r-process calculations from merger scenarios they considered following five fluid trajectories with the initial conditions:
Ye^I → initial electron fraction,
s → initial entropy,
τ → expansion time scale within the material covering

- dynamical ejecta both at Polar (DynPo) and Equatorial angles (DynEq)
- neutrino- driven Wind ejecta (DisWN)
- Viscosity-driven Wind ejecta (SisWV)

Adopting the combination (Ye^I, s, τ) as
(0.05, 8, and 10) → for dynamical ejecta at equatorial latitudes;
(0.35, 30, and 10) → for dynamical ejecta at Polar latitudes;
(0.30, 20, and 10) → for the spiral-wave wind ejecta;
(0.35, 15, and 30) → for the neutrino-driven disk wind ejecta;
(0.25, 20, and 80) → for the viscous ejecta
the significant results of the final abundances in comparison to the solar r-process residuals they obtained for the evolved period up to 10Myr (Figure 4) are:

i. The overall fact is that the ensemble of trajectories is able to reproduce (approximately) all the data ranging up to the heaviest nuclei. In particular, the DynEq ejecta produce a full r-process pattern with the second and third r-process peak elements such that the relative abundances are very close to that of the solar process.
ii. Actinide4s are well produced with significant amount.
iii. The ejecta of other cases i.e. DynPo, SpiWW, and DisWN follow the path leading to a weak r-process path i.e., produce the light r-process elements, while DisWV shows its influence up to producing the second r-process peak with no lanthanides production.

Conclusion

Production of heavy elements via r-process by the new born magnetar, associated with supernova and binary neutron star merger, offers the astronomers to search the exact location of the magnetar via x-ray lines. Using gravitational wave radiation neutron star binary merger event GW170817 was detected by LIGO and Virgo. This detection confirms the answers of many long-standing questions:

a. Existence of binary neutron star and their merger event in the universe;
b. New form of one of the neutron star components in binary merger;
c. Short GRBs are associated with this merger event;
d. Origin of r-process abundances during the merger and post-merger events, etc.

But the main unsolved area remains on the exact location of magnetar, the creator of r-process abundances, its birth time, etc. Recently detected Cosmic Baby i.e. Swift J1818.0 – 1607 have immense possibility to answer many questions arises from neutron star binary merger event. In binary merger event many realistic phases / situations are still remain hidden or beyond the detectable range. We are hopeful that thorough observation of Cosmic Baby via electromagnetic radiation (i.e. x-ray, gamma ray) as well as gravitational wave radiation may unravel the secrets of the binary event merger.

Acknowledgement

The author expresses his sincere gratitude to the anonymous referee for his / her valuable comments and suggestions for improvement the quality of the manuscript. He is greatly indebted to Dr Ramon Clerk for his kind invitation and encouragement.

He also wishes to thank Prof. H. N. K. Sarma, Dept. of Physics, Manipur University; Mr B. K. Ganguly, Airports Authority of India, Kolkata, Mrs. Tapati Parui and Mr Rajarshi Parui for their various helps during the preparation of the manuscript.

Data Availability: Data sharing is not applicable as no datasets were used / analyzed.

Competing Interest: The author declares no competing interests.

Ethical Conduct: Not applicable.

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