The Astrophysical Journal Letters, 881:L4 (4pp), 2019 August 10 https://doi.org/10.3847/2041-8213/ab3215

Early Solar System r-process Abundances Limit Collapsar Origin

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Received 2019 June 25; revised 2019 July 8; accepted 2019 July 12; published 2019 August 5

Abstract

Heavy elements produced exclusively through rapid neutron capture (the "r-process") originate from violent cosmic explosions. While neutron star mergers are the primary candidates, another plausible production site are "collapsars"—collapsing massive stars that form a black hole with an accretion disk. Here we show that collapsars are too rare to be the prime origin of r-process elements in the solar system. By comparing numerical simulations with the early solar system abundances of actinides produced exclusively through the r-process, we exclude higher than 20% contribution from collapsars with 90% confidence. We additionally limit r-process ejecta masses from collapsars to less than 10% of the ejecta mass from neutron star mergers, about $10^{-2}\,M_{\odot}$.

Unified Astronomy Thesaurus concepts: Neutron stars (1108); Nucleosynthesis (1131); Gravitational wave sources (677); Stellar nucleosynthesis (1616); Core-collapse supernovae (304)

1. Introduction

The cosmic creation of heavy r-process elements is still not well understood. Core-collapse supernovae, which were historically considered to be the main source (Burbidge et al. 1957; Woosley et al. 1994), are too frequent to explain the measured isotopic abundances in the early solar system, in deep-sea sediments, and in metal-poor stars (Hotokezaka et al. 2015; Wallner et al. 2015; Macias & Ramirez-Ruiz 2018; Bartos & Marka 2019).

Neutron star mergers are natural candidates as a major production site. They eject high-density, neutron-rich matter in sufficient quantities to be the main source of Galactic r-process elements (Goriely et al. 2011; Shen et al. 2015; van de Voort et al. 2015). This possibility is further corroborated by recent multi-messenger observations of a neutron star merger accompanied by a kilonova (Abbott et al. 2017; Coulter et al. 2017). The rate of neutron star mergers in the Milky Way is 10–100 Myr^{-1} (Pol et al. 2019), about a 1000 times less than the rate of supernovae (Tammann et al. 1994), which is consistent with expectations from isotopic abundances in the early solar system and deep-sea sediments (Hotokezaka et al. 2015; Wallner et al. 2015; Bartos & Marka 2019).

Rare source types other than neutron star mergers may also contribute to r-process enrichment. Collapsars are stellar core-collapse events that have sufficiently massive cores to form black holes, and sufficient angular momentum at the time of collapse to form an accretion disk (MacFadyen & Woosley 1999). The resulting accreting black holes could produce r-process elements through disk winds similarly to neutron star mergers (Pruet et al. 2004; Kohri et al. 2005; Siegel et al. 2019).

Collapsars are only expected in stars with low metallicities, while neutron star mergers are delayed compared to star formation. Therefore, a collapsar origin could help explain the presence of r-process elements in extremely metal-poor stars, which is more difficult with neutron star mergers (Ji et al. 2016; Côté et al. 2017; Safarzadeh et al. 2019). On the other hand, the observed r-process enrichment of some metal-poor stars disfavors sources like collapsars that are significant metal producers (Macias & Ramirez-Ruiz 2019). Additional challenges to the neutron star mergers as the main r-process production site include the strong enhancements in heavy r-process elements of some stars in ultra-faint dwarf galaxies (Ji et al. 2016; Hansen et al. 2017), as the low escape velocities and short star formation epochs in such galaxies would require unusually small natal kick velocities and fast merger time (Siegel 2019). Further, Galactic r-process enrichment at high metallicities appears to be slower than expected from neutron star mergers, although this is dependent on the uncertain event rate and time delay compared to star formation (Côté et al. 2017; Hotokezaka et al. 2018).

We examined the origin of r-process elements in the early solar system by considering fractional contributions from both neutron star mergers and collapsars. We used the abundances of short-lived radioactive isotopes that encode information on their production and deposition history. Even though these elements are by now extinct in the solar system, meteorites that condensed during the early solar system still carry their imprint (Nittler & Dauphas 2006). The early solar system abundance of a short-lived radioactive isotope (N_{SLR}) can be estimated by comparing the abundance of its decay product with that of a chemically identical isotope (N_{stable}). The measured abundance ratio $N_{\mathrm{SLR}}/N_{\mathrm{stable}}$ relative to the elements' production ratio $P_{\mathrm{SLR}}/P_{\mathrm{stable}}$ tells us the time interval between the astrophysical event that synthesized the elements and the formation of the solar system.

2. Methods

2.1. Abundances

The ratios of the abundances of different elements produced in the ejecta are taken to be their production ratios. Here, we adopted estimates of production ratios found in Tissot et al. (2016; see also Bartos & Marka 2019). For ^{247}Cm and ^{244}Pu we used another actinide, ^{232}Th, as our reference isotope. ^{232}Th is long-lived with $t_{1/2} = 1.4 \times 10^{10}$ yr, therefore it is still detectable in remnants from the early solar system. Our reference isotope for ^{129}I is another r-process product, ^{127}I, which is stable. For ^{129}I, for which Tissot et al. (2016) obtained the ratios by averaging the results of multiple previous studies,

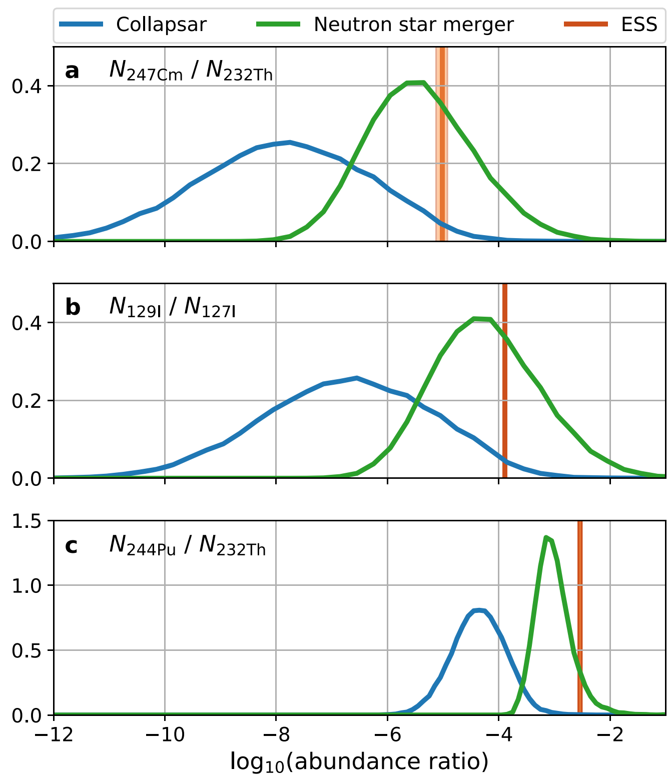

Figure 1. Simulated and measured abundance ratios. Ratios $N_{^{247}\mathrm{Cm}}/N_{^{232}\mathrm{Th}}$ (top), $N_{^{129}\mathrm{I}}/N_{^{127}\mathrm{I}}$ (middle) and $N_{^{244}\mathrm{Pu}}/N_{^{232}\mathrm{Th}}$ (bottom) in the early solar system are shown for simulated collapsar and neutron star merger populations, along with the measured values (see legend). The shaded area around the measured values represent 1σ uncertainties.

we adopted the mean difference between the average value and the values of these studies.

We adopted early solar system abundance ratios for ^{247}Cm and ^{244}Pu from Tissot et al. (2016), and for ^{129}I from Lugaro et al. (2018).

2.2. Collapsar Rate in the Milky Way

Long gamma-ray bursts (GRBs) occur in low-metallicity, highly star-forming environments (Woosley & Heger 2006). Ongoing star formation is important because massive stars that produce collapsars only live for a few million years, while low-metallicity limits stellar winds that would otherwise reduce the star's mass before collapse. These requirements make collapsars rare in the Milky Way (Fruchter et al. 2006; Langer & Norman 2006).

To estimate the Galactic rate of collapsars as a function of time, we consider its dependence on metallicity and star formation rate in the Milky Way. For fixed metallicity, we assume that the collapsar rate is proportional to the core-collapse supernova rate. Based on the fraction of stars in the Milky Way that have low metallicities similar to long-GRB host galaxies, the Galactic collapsar rate at present is expected to be about 5% of the collapsar rate in the local universe implied by star formation only (Piran & Jimenez 2014). We extend this 95% metallicity suppression by assuming that the collapsar rate is suppressed by $0.95Z(t)/Z(t_0)$, where $Z(t)$ is the Galactic metallicity at time t, with t_0 being the present day. The precise shape of this suppression does not meaningfully affect our results. We adopt the metallicity evolution of the Milky Way from Hayden et al. (2015; see their Figure 9. We chose their result at 4 kpc as that region has the highest star formation; the difference is not large at different radii).

We assume that all collapsars produce a long GRB. We take a local long GRB rate of 1.3 Gpc^{-3} yr^{-1} (Wanderman & Piran 2010). Using a characteristic long GRB beaming factor of 5×10^{-3} defined as the fraction of the sky in which a GRB can be observed from cosmological distances (Goldstein et al. 2016), the corresponding local collapsar rate is $\sim$260 Gpc^{-3} yr^{-1}. The local star formation rate density is $\sim 10^7\ M_\odot$Gpc^{-3} yr^{-1} (Cucciati et al. 2012), while the present star formation rate in the Milky Way is $\sim 1\ M_\odot$yr^{-1} (Prantzos & Silk 1998).

Combining these, we arrive at a present Galactic collapsar rate of $\sim$1 Myr^{-1}. Beyond taking into account the metallicity suppression above, we computed the past collapsar rate by additionally taking into account the evolution of the core-collapse supernova rate in the Milky Way. We adopted the Galactic core-collapse supernova rate as a function of time based on the high-resolution, zoom-in cosmological simulation of a the Milky Way analog called Eris (Guedes et al. 2011), computed by Shen et al. (2015).

2.3. Neutron Star Merger Rate in the Milky Way

We adopted the Galactic rate of neutron star mergers as a function of time based on the Eris simulation (Guedes et al. 2011), computed by Shen et al. (2015). This rate varies within about 5–10 Myr^{-1} over the history of the Milky Way, which is consistent with population synthesis estimates (Shen et al. 2015; Artale et al. 2019).

2.4. Monte Carlo Simulations

In one Monte Carlo realization of the Milky Way, neutron star mergers and collapsars were randomly placed in space and time using the above rates throughout the lifetime of the Galaxy. The spatial probability distribution of the neutron star merger followed the Galactic stellar mass distribution (McMillan 2011). Collapsars were placed randomly following a probability density that is radially proportional to the Galactic star formation rate, with no azimuthal dependence, and with a scale height of 80 pc (Robitaille & Whitney 2010).

We simulated the chemical mixing of r-process elements following Hotokezaka et al. (2015), accounting for radioactive decay and turbulent diffusion within the Milky Way with diffusion coefficient

$$D \approx 0.1\ \mathrm{kpc}^2\ \mathrm{Gyr}^{-1}\left(\frac{\alpha}{0.1}\right)\left(\frac{v_t}{7\ \mathrm{km\ s}^{-1}}\right)\left(\frac{H}{0.2\ \mathrm{kpc}}\right) \quad (1)$$

where α is the mixing length parameter, v_t is the typical turbulence velocity in the interstellar medium (ISM), and H is the ISM-scale height. We adopt $D = 0.1$ kpc^2 Gyr^{-1} below following Hotokezaka et al. (2015; see also Yang & Krumholz 2012). We used identical ejecta mass and composition for all mergers and, independently, all collapsars. Abundance ratios in the early solar system were taken to be proportional to abundance ratios in the ISM near the pre-Solar nebula at the time of the formation of the solar system. We assumed that the time between deposition into the pre-Solar nebula and the condensation of meteorites that preserved the imprint of short-lived isotopes in the early solar system is negligible (Dauphas & Chaussidon 2011; Tang et al. 2017).

We obtained the probability distribution of actinide abundance ratios in the early solar system by varying the time when the solar system was formed between 8 and 9 Gyr within a Monte Carlo realization of the Milky Way, and by computing 10^3 realizations.

3. Results

3.1. Comparison of Expected Abundance Ratios

We carried out Monte Carlo simulations of neutron star mergers and collapsars in the Milky Way to calculate the expected *r*-process abundances in the early solar system (Hotokezaka et al. 2015; Bartos & Marka 2019). We computed the abundances of Curium-247 (^{247}Cm; half-life $t_{1/2} = 15.6$ Myr), Iodine-129 (^{129}I; $t_{1/2} = 15.7$ Myr) and Plutonium-244 (^{244}Pu; $t_{1/2} = 80.8$ Myr) separately, normalized by the abundances of long-lived *r*-process elements such that the obtained abundance ratios could be compared to measured early solar system values. The results, shown in Figure 1, are instructive. We see that the abundance ratio probability densities for neutron star mergers are distributed around the early solar system values. As collapsars are more rare and, their expected contribution to the short-lived abundances is diminished, resulting in a probability distribution that is mostly much below the measured value. In addition, the collapsar rate of the Milky Way was significantly higher in its early period much before the formation of the solar system. This injected long-lived elements into the Milky Way, further reducing the abundance ratios at the time of the solar system's formation.

3.2. Limit on the Fractional Collapsar Contribution

We computed the probability density of the fraction f_c of *r*-process elements from collapsars in the solar system. We randomly selected simulated early solar system abundances from both the collapsar and the neutron star merger simulations, and combined them such that collapsars contribute f_c fraction of the total stable *r*-process elements. We then checked whether this combination reproduces the measured early solar system abundance ratios to within $\pm 30\%$. The probability density of a given f_c was taken to be proportional to the fraction of simulated abundances that satisfy this criterion.

The resulting cumulative probability densities are shown in Figure 2. We show these densities both by requiring that the abundance ratios of either a single or all elements match the measured values. From the distributions for individual mass ratios, we see that collapsar contribution is particularly constrained by ^{244}Pu.

To explain this, we used our simulations to compute the average fraction of different isotopes in the early solar system that came from collapsars, as a function of f_c. The obtained fractions are shown in Figure 3. We see that the fraction of long-lived isotopes is similar to f_c, while we find a limited collapsar contribution to ^{244}Pu, and essentially no contribution to ^{247}Cm and ^{129}I.

By requiring all simulated abundance ratios to simultaneously match the measured early solar system values, we see in Figure 2 that a collapsar contribution $\gtrsim 20\%$ to *r*-process elements is excluded at 90% confidence level.

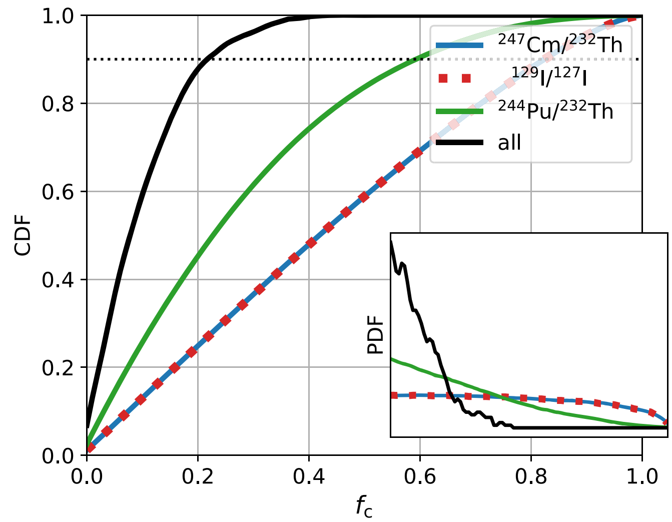

Figure 2. Cumulative probability density of fractional collapsar contribution. CDFs of the simulations agreeing with measured ratios are shown separately for $N_{^{247}\mathrm{Cm}}/N_{^{232}\mathrm{Th}}$, $N_{^{129}\mathrm{I}}/N_{^{127}\mathrm{I}}$, and $N_{^{244}\mathrm{Pu}}/N_{^{232}\mathrm{Th}}$ and by requiring that all three agree with observations within 30% (see the legend). The corresponding probability densities are shown in the subplot on the lower right. The horizontal dotted lines indicates 90%.

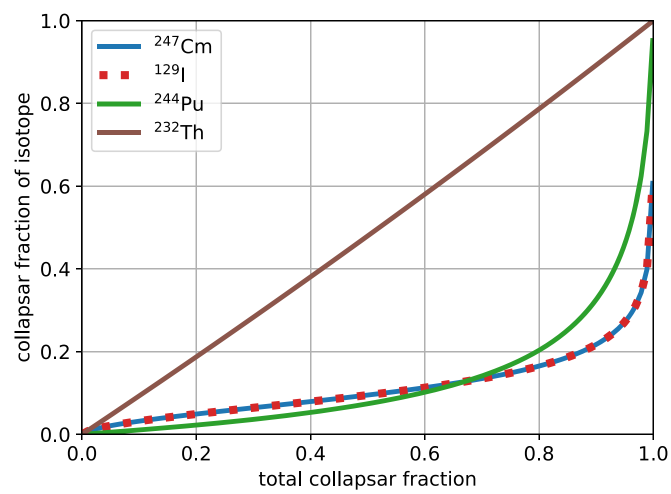

Figure 3. Fractional collapsar contribution to short-lived *r*-process elements. The simulated fractions of ^{247}Cm, ^{129}I, and ^{244}Pu (see the legend) from collapsars in the early solar system are shown as functions of the overall fractional contribution f_c of collapsars for all *r*-process elements.

3.3. Limits on the Collapsar Ejecta Mass

Using our simulations we can convert the fractional collapsar contribution f_c to the early solar system to an estimate on the collapsar *r*-process ejecta mass. For this, we measured from our simulation the *r*-process density near the early solar system from collapsars and neutron star mergers, in both cases normalized by their respective ejecta mass. By fixing the required collapsar fraction, we can use these abundances to find the relative ejecta masses for the two source types. We find that For $m_{\mathrm{ej,c}}$ and $m_{\mathrm{ej,ns}}$ *r*-process ejecta masses, for collapsars and neutron star mergers, respectively, we find

$$m_{\mathrm{ej,c}} \approx m_{\mathrm{ej,ns}} \frac{0.6 f_c}{1 - f_c}. \quad (2)$$

Taking our exclusion limit of $f_c] \lesssim 0.2$, this means that $m_{ej,c} \lesssim 0.15 m_{ej,ns}$. Assuming that $m_{ej,ns} < 0.1\ M_\odot$ (Siegel 2019), we obtain $m_{ej,c} \approx 0.01\ M_\odot$.

4. Conclusion

We found that the measured early solar system abundances of short-lived *r*-process elements (^{244}Cm, ^{129}I, and ^{244}Pu) are typical for a neutron star merger population, while they are unlikely from a collapsar population.

Considering contributions from both neutron star mergers and collapsars, we find that a more than 20% collapsar contribution is excluded at 90% confidence level for our model. This limit is due to the lower rate of collapsars compared to mergers, and their higher relative rate in the early Milky Way compared to the time of the formation of the solar system.

Using the above limit on the fractional *r*-process contribution from collapsars and the computed deposition rate in our simulations, we exclude *r*-process ejecta masses from collapsars great than $10^{-2}\ M_\odot$.

The observational limits on the *r*-process ejecta mass from collapsars suggests that outflows from collapsar disks may produce less *r*-process matter than previously thought (Siegel et al. 2019). It is also possible that collapsar outflows are less neutron rich and therefore only produce lighter *r*-process elements, but not actinides. Alternatively, a currently unknown sub-population of collapsars that do not produce GRBs would mean a higher collapsar rate considered here that would allow a higher overall fractional collapsar contribution. The results presented here will help convert future observations of kilonovae from neutron star mergers to probe the rate of collapsars, their connection to GRBs, and the properties of accretion disks.

The authors thank Enrico Ramirez-Ruiz and Mohammad Safarzadeh for their useful feedback. The authors are grateful for the generous support of the University of Florida and Columbia University in the City of New York.

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