A Stringent Limit on the Mass Production Rate of $r$-process Elements in the Milky Way

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Received 2016 September 13; revised 2018 May 8; accepted 2018 May 8; published 2018 June 15

Abstract

We analyze data from several studies of metal-poor stars in the Milky Way, focusing individually on the main $r$-process elements (Eu) as well as the lighter neutron-capture element Sr, at the neutron-magic peak $N = 50$. Because these elements were injected in an explosion, we calculate the mass swept up when the blast wave first becomes radiative, yielding a lower limit for the dilution of such elements and hence a lower limit on the ejecta mass that is incorporated into the next generation of stars. Our study demonstrates that in order to explain the largest enhancements in [Eu/Fe] observed in stars at low [Fe/H] metallicities, individual $r$-process production events must synthesize a minimum of roughly $10^{-3} M_\odot$ of $r$-process material. This provides a critical constraint on galactic chemical evolution models. We also show independently that if the site of Mg production is the same as that of Eu, individual injection events must synthesize up to $\sim 10^{-3} M_\odot$ of $r$-process material. On the other hand, demanding that Sr traces Mg production results in $r$-process masses per event of $\sim 10^{-5} M_\odot$. This suggests that the astrophysical sites responsible for the genesis of the main $r$-process elements need to operate at a drastically reduced rate when compared to standard core-collapse supernovae.

Key words: Galaxy: abundances – nuclear reactions, nucleosynthesis, abundances – stars: abundances – stars: neutron

1. Introduction

Although the physical conditions required for $r$-process nucleosynthesis to occur have been understood since Burbidge et al. (1957) and Cameron (1957), the astrophysical site(s) in which these conditions are realized remains unclear. Whether enrichment has occurred via Type II supernovae (SNe, e.g., Woosley et al. 1994), in which the injection in a galaxy occurs frequently ($\sim 10^{-2} \text{yr}^{-1}$) with low ($\sim 10^{-3} M_\odot$) masses, or through sporadic ($\sim 10^{-5} \text{yr}^{-1}$) injection by neutron star mergers (NSM, e.g., Lattimer & Schramm 1974) of high ($\sim 10^{-2} M_\odot$) masses is difficult to discern at high metallicities, as any hysteresis has been eradicated by multiple enrichment events.

For this reason, metal-poor stars in the galactic halo serve as laboratories for the study of $r$-process element synthesis and can shed light on the identity of their progenitors (Snedden et al. 2008). Abundance comparisons between many metal-poor halo stars suggest that the $r$-process mechanism is rather robust. In other words, we see the same relative proportions of $r$-process elements in stars that are many billions of years different in age, indicating that this process has operated in a fairly consistent manner throughout the history of the Galaxy. This result provides critical information regarding the specific physical conditions resulting in the nuclear pathways required for the $r$-process.

In the metallicity range [Fe/H] of roughly $-2$ to $-3.5$, where we are using the standard notation $[X/H] = \log_{10}(X/H) - \log_{10}(X/H)_{\odot}$, $r$-process elements have been found to exhibit large star-to-star bulk scatter in their concentrations with respect to the lighter elements, but with a distribution that is characteristic of solar system matter. This hints at the presence of chemically inhomogeneous and unmixed gas at that epoch (Fields et al. 2002). As time evolves, these localized inhomogeneities are smoothed out as more events occur and $r$-process products migrate and mix throughout the Galaxy. Recently, “zoom-in” cosmological simulations of heavy element production in a Milky Way-like (MW-like) galaxy have shown the observed stellar abundances resulting from this process to be consistent with NSMs being the dominant enrichment mechanism (Shen et al. 2015; van de Voort et al. 2015; Naiman et al. 2018), but must rely on prescriptions regarding how material is mixed in the young MW and suffer from uncertainties in the delay time for NSMs.

In this paper we use simple and conservative physical arguments to show that the scatter in Eu and lighter neutron-capture elements such as Sr at low [Fe/H] metallicities can be used to place stringent lower limits on how much $r$-process material needs to be synthesized per injection event in the early Universe. In Section 2 we combine abundance data from several previous studies of MW stars and focus on Mg production to identify stars that may have formed from gas that has been enriched by no more than a few nucleosynthetic events. In Section 3 we derive lower limits on the $r$-process production required to explain Eu enhancements in these same stars, and also demonstrate the implications of demanding that $r$-process enhancements trace the Mg source. In Section 4 we discuss our findings and explore the possibility of distinguishing between rare events by considering the environment in which they may take place.

2. Supernova II as Testbeds for Metal Enrichment

While there is no current consensus on the dominant channel of $r$-process production, it is well understood that the so-called $\alpha$ (O, Mg, Si, Ca, and Ti) elements are primarily produced in massive stars and returned to the interstellar medium (ISM) via core-collapse SNe (Burbidge et al. 1957; Woosley & Weaver 1995). For this reason, elements such as Mg have been measured in metal-poor MW halo stars to study the efficiency of galactic mixing in the early universe (Arnone...
Here we focus on Mg production in the MW in order to demonstrate how our physical argument applies to a relatively well-understood production source.

SNe input approximately $10^{51}$ erg of energy into their surroundings, resulting in a blast wave that sweeps up a less $\alpha$-enhanced ISM, thereby mixing and diluting any enhancement supplied by the ejecta. In order to incorporate these metals into a new generation of stars, the SN blast wave must first cool, at the very least. The mass swept up before the blast wave becomes radiative and cools efficiently in a homogeneous medium and is given by

$$M_{\text{cool}} \approx 10^{3} \left( \frac{Z}{Z_{\odot}} \right)^{-3/7} \left( \frac{n_{\text{ISM}}}{10^{2} \text{ cm}^{-3}} \right)^{-2/7} \left( \frac{E_{\exp}}{10^{51} \text{ erg}} \right)^{6/7} M_{\odot},$$

where $E_{\exp}$ is the explosion energy, and $Z$ and $n_{\text{ISM}}$ are the metallicity and number density of the surrounding ISM, respectively (Cioffi et al. 1988; Thornton et al. 1998; Martizzi et al. 2015). For a given ejecta mass, the maximum enhancement possible of the surrounding ISM (to be observed in the next generation of stars) occurs when the ejecta has mixed with $M_{\text{cool}}$, as further mixing (which inevitably occurs due to the inertia of the expanding material as well as larger-scale mixing due to, e.g., turbulence generated by galactic shear) will further dilute the enhancement (Greif et al. 2009).

One can then invert this relation to find the minimum mass of the event for a given enhancement in the next generation of stars, which is given by

$$M_{X} \geq X_{\odot} \times 10^{[X/H]} M_{\text{cool}},$$

where $X_{\odot}$ is the mass fraction of element $X$ within the Sun. This is the mass required to explain a given stellar enhancement, assuming the ejecta is only mixed within a cooling mass. Since the ejecta certainly mixes with greater than a cooling mass and further dilutes, Equation (2) represents a strict lower limit for low-metallicity stars that have not been enriched by multiple events. Recent hydrodynamical simulations show final swept-up masses between 1700 $M_{\odot}$ in a homogeneous ISM and 8000 $M_{\odot}$ in a turbulent ISM with similar scalings, indicating that our analytical estimate is conservative (Martizzi et al. 2015).

In Figure 1 we plot [Mg/Fe] as a function of [Fe/H] for a compilation of MW stars and show in color the minimum $M_{\text{Mg}}$ required to explain the observations, assuming that the ISM that collapsed to form the stars was enhanced by a single event that input $10^{51}$ ergs of energy. This simplistic assumption clearly breaks down at high metalicities where the gas has been enhanced by many events throughout the history of the galaxy, but we note some interesting behavior at low metallicity. First, at [Fe/H] $\lesssim -2.5$, the stars are all consistent with a minimum Mg mass lower than 0.1 $M_{\odot}$, which is shown by the dashed line and is roughly in agreement with the Mg mass expected to be produced in a single, standard core-collapse SN (Kobayashi et al. 2006; Nomoto et al. 2006). We do not expect a clustering at exactly the dotted line as the SNe likely mix well past their cooling mass, resulting in a vertically downward trajectory in the plot. At higher metalicities, we see a convergence toward [Mg/Fe] = 0.5, which is roughly the IMF-weighted yield of SN ejecta (e.g., Kobayashi et al. 2006). At this point, the gas is well mixed and is clearly incompatible with pollution by a single event, as further evidenced by the high masses required to explain the enhancement.

The dearth of stars in the upper right quadrant is easy to understand. At the lowest metallicities, star-forming gas is unlikely to have been polluted by more than the mass of a single event (shown by the diagonal dashed line), while at higher metalicities, it is impossible to be enriched beyond the yields since the mass fraction is an intensive quantity, i.e., the enrichment has converged to the yields.

Because we wish to constrain the mass per event of $r$-process material, we do not consider this integrated history and instead focus our attention on metallicities lower than that in which the enriched gas has reached [Mg/Fe] abundance ratios close to those given by SN yields ([Fe/H] $< -2.5$).

3. Constraints on $r$-process Production

3.1. A Strict Lower Limit

With the data set now consisting of only these low-metallicity single-event candidates, we can begin to ask more probing questions. First, we can repeat exactly the same exercise as for Mg on a so-called $r$-process-only element, Eu, for the same set of stars. At these low metallicities, heavier elements such as Eu certainly cannot have saturated to the yields, as the overall mass production rate of Mg exceeds that of Eu by several orders of magnitude. Because the main $r$-process pattern has been shown to be robust, we can then scale the Eu mass to a total $r$-process mass within the second and third peaks demanded by the Eu abundances.

For these scalings, we use a total solar $r$-process mass fraction of $X_{r,p,\odot} = 3.5 \times 10^{-7}$ (with $3.6 \times 10^{-10}$ in Eu), which is composed of 78% light (first peak) and 22% in the main component (Arnould et al. 2007). We distinguish the boundary between light and main at a mass number $A$ of 90. This analysis does not depend on the initial ejecta configuration (e.g., spherical ejections as opposed to tidal tails), as the initial conditions are quickly forgotten and the explosion finds the standard, spherical Sedov–Taylor blast wave solution long before reaching the cooling radius (Montes et al. 2016).
We assume a total $r$-process mass production rate of $M_{r,p} \approx 10^{-7} M_\odot$ yr$^{-1}$, which is consistent with observations (Cowan & Thielemann 2004; Sneden et al. 2008). For an SN rate of $10^{-2}$ yr$^{-1}$, the mass per event required to be consistent with $M_{r,p}$ is $7.8 \times 10^{-6} M_\odot$ for the first peak, $2.2 \times 10^{-6} M_\odot$ for the main component, and thus $10^{-5} M_\odot$ in total.

For a current compilation of heavy element measurements in low-metallicity stars, we use the SAGA database (Suda et al. 2008), which compiles literature results and ensures consistency in, e.g., solar abundance values. Figure 2 shows the result of this experiment. We find that if the events that caused the Eu enhancement formed the next generation of stars at the cooling mass of the blast wave, these events would correspond to a total $r$-process mass of up to $10^{-3} M_\odot$. We emphasize that each one of these points is a minimum mass per event, and thus represent lower limits. Most of our data are inconsistent with the $2.2 \times 10^{-6} M_\odot$ per event (shown by the horizontal dashed line) necessary to produce the total main $r$-process content in the Galaxy given an average SN rate of $10^{-2}$ yr$^{-1}$.

The mass-weighted, cumulative histogram shown in projection at the right can be read as stating that although a significant fraction of stars do not contradict a production rate of $10^{-2}$ yr$^{-1}$ or more, essentially all of the mass production must come from less frequent events.

We can perform this same experiment on Sr, a lower mass element that may be produced in a less neutron-rich environment, e.g., a neutrino-driven wind (e.g., Arcones & Montes 2011), in order to infer upper limits on the event/injection rate of the lighter first-peak $r$-process elements. Figure 3 shows the result of this experiment. Unlike Eu, we find that Sr is marginally consistent with a mass per event of $\lesssim 7.8 \times 10^{-6} M_\odot$, resulting in an average injection rate of $\gtrsim 10^{-2}$ yr$^{-1}$. This implies that standard CCSNe are consistent with being a significant source of first-peak $r$-process material given their rate, in contrast to our Eu findings. However, we note that several stars, and roughly half of the total inferred mass, are inconsistent with this rate. Again, considering that these inferred masses can only move upward under our assumptions, this may imply large variations from event to event, or multiple progenitor channels. Recently, several studies have indicated that there may be multiple sites for the first peak, which these discrepancies may also be pointing toward.

### 3.2. Constraints Based on Mg Mixing

We now return our attention to our original sample of stars with Mg and Eu measurements from Section 2 and attempt to place constraints under the assumption of the Mg and $r$-process elements coming from the same source. Numerical simulations of SN nucleosynthesis have provided us with the average amount of Mg mass ejected in SNe across a wide range of progenitor masses and metallicities (e.g., Kobayashi et al. 2006). Similar to Fields et al. (2002), with these results we can calculate the mixing mass (denoted here as $M_{\text{mix}}$), i.e., the ISM mass over which the Mg must be diluted in order to explain the observed stellar abundances if the subsequent generation of stars were formed by gas that was enriched by a single pollution event,

$$M_{\text{mix}} = 130 \times 10^{-[\text{Mg/Fe}]} \left( \frac{M_{\text{Mg}}}{0.1 M_\odot} \right) M_\odot,$$ (3)
At these low metallicities, we do not consider the environment, which is realized in either SNe, NSMs, or both. Metallicity. Eu is shown with red symbols, and black symbols show the abundances assuming it mixes over the same mass as the Mg as a function of where we have used Figure 5. Total

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Figure 5. Total r-process mass per event required to explain the stellar abundances assuming it mixes over the same mass as the Mg as a function of metallicity. Eu is shown with red symbols, and black symbols show the inferred masses for Sr. The markers at the top left are not detections.

where we have used $X_{\text{Mg},\odot} = 7.2 \times 10^{-4}$ (Lodders 2003) and a fiducial SN Mg mass of 0.1 $M_\odot$. The normalization for the mixing mass is not to be taken at face value since the galaxy is well mixed in $\alpha$ elements at [Mg/H] = 0. Figure 4 shows our reduced sample, now in color showing $M_{\text{mix}}$ for a fiducial SN Mg mass of 0.1 $M_\odot$. We can then use the ansatz that the source of the Mg is the same as that of both Eu and Sr. As mentioned before, Sr (unlike Eu) may be synthesized in a less neutron-rich environment, which is realized in either SNe, NSMs, or both. At these low metallicities, we do not consider the s-process from asymptotic giant branch stars to contribute to the observed Sr abundances, although massive low-metallicity rotating stars may contribute to a primary s-process (Pignatari et al. 2008; Frischknecht et al. 2016). While our findings could in principle be used to place constraints on the production efficiency of this channel at low metallicities, we do not attempt this exercise here.

If these elements are coming from the same astrophysical site, this mixing mass should be the same for Eu and Sr as for Mg, allowing us to infer a total r-process mass per event. With this assumption, we can perform the same exercise as before, now replacing the cooling mass with the mixing mass as our reference mass scale. If the source of Mg is responsible for creating the entirety of the r-process elements, we can again convert from an elemental mass to total r-process mass by scaling the relative abundances to match the solar values, i.e.,

$$M_{r-p} = X_{r-p,\odot} \times 10^{[\text{Eu/H}]} M_{\text{mix}}.$$  (4)

However, if the Mg source is only responsible for the lighter, first-peak elements, we have instead

$$M'_{r-p} = f_I X_{r-p,\odot} \times 10^{[\text{Sr/H}]} M_{\text{mix}},$$  (5)

where we use $X_{r-p,\odot} = 3.5 \times 10^{-7}$, and $f_I$ is the fraction of total r-process mass in the light r-process element ranges, as defined in Section 3.1.

Mixing is element agnostic, so we can test the consequences of this hypothesis and answer the question of r-process production required by SN in order to explain the observed abundances at low metallicities. Figure 5 shows the results. For Sr, demanding that the source of Mg production in the early universe also produces the first r-process peak elements results in masses well above the $7.8 \times 10^{-6}$ required to have the mass per event consistent with an average SN rate of $10^{-2}$ yr$^{-1}$.

These results may be of particular interest, as first-peak r-process elements have been successfully synthesized in SN nucleosynthesis calculations for some time as well as in recent NSM simulations (Martin et al. 2015; Wu et al. 2016). In the NSM case, the main r-process elements are robustly synthesized in the initial dynamical ejecta. However, a remnant accretion disk around a hyper-massive neutron star (HMNS) or black hole may provide the conditions for creation of the first-peak elements. The mass of this component remains uncertain to within orders of magnitude and is very sensitive to several parameters, e.g., the lifetime of the HMNS.

For Eu, we wish to test a Mg source that would also create all r-process peaks, not only second and third. As seen in Figure 5, the demand that Eu (and hence the entirety of the r-process elements) traces the Mg results in total r-process masses well above $10^{-5} M_\odot$. This serves as proof by contradiction: requiring that the channel providing Mg enrichment in the early universe is the same as that which provides Eu would drastically overproduce the total r-process mass in the galaxy today.

We note that $M_{\text{mix}}$ should be inversely proportional to the rate of injection, i.e., that rarer events will be spread out farther in distance as well as time, and will thus dilute further between events, e.g., through turbulent diffusion. In this way, this experiment implies another lower limit on $M_{\text{p}}$. Any event that is rarer implies a mass per event higher than seen in Figure 5, and any event with higher rates would overproduce the galactic r-process even more drastically.

4. Discussion

By looking at metal-poor stars in the MW, we are able to place strong constraints on the mass per event and hence rate of the events that have enriched them in r-process elements. As seen in Figure 2, essentially all of the main r-process mass in the galaxy must have been synthesized in events that output $\geq 2.2 \times 10^{-6} M_\odot$ of material, translating into a rate of $< 10^{-3}$ yr$^{-1}$ in order to match $M_{\text{p}}$. This shows that even under the most conservative assumptions, core-collapse SNe are inconsistent with being the dominant progenitor of main r-process elements in the early universe given their frequency. On the other hand, our results for Sr show that this channel could still produce a sizable fraction of the light r-process elements.

Our conclusions regarding the main r-process are in agreement with several recent arguments, as it is only in the past few years that observations have allowed us to break the degeneracy between rate and mass per event among the leading theories by looking farther back into the history of the galaxy (e.g., Shen et al. 2015; Ji et al. 2016a). In addition, we have used a fiducial density of $10^2$ cm$^{-3}$ in our calculation of $M_{\text{cool}}$, whereas NSMs are likely to occur in regions of lower density if they receive a kick from the SNe that created the pair (e.g., Belczynski et al. 2006; Kelley et al. 2010). From Equation (1), lowering the ambient density by a factor of 100 increases the mass per event by a factor of 4, implying an r-process mass of $\geq 10^{-3} M_\odot$ per event.

Beniamini et al. (2016b) have recently performed a similar analysis using ultra-faint dwarf galaxies (UFDs), assuming a gas mass for the galaxy and calculating the Eu (and hence total
the r-process) mass required to explain the observed stellar abundances. Their result is in agreement with ours, i.e., they find that the Eu mass per event is inconsistent with enrichment from typical core-collapse SNe given their rate, which naturally extends itself to MW stars assuming the dominant mechanism is the same in both galaxy types. This assumes that the ejecta are well mixed throughout the UFD gas, an assumption that we also require at the cooling mass scale, although this is well justified as SN remnants show efficient mixing well before the cooling mass is reached (Lopez et al. 2011). Even though inhomogeneous mixing may take place at larger scales, this will not re-concentrate a given element. However, our analysis demands an even more conservative lower limit on the r-process mass per event, as most of our cooling masses are below the fiducial \(10^5 \, M_\odot\) UFD gas mass.

Through independent means, we are able to look at both the first-peak and main r-process elements and calculate the total r-process mass implied by assuming that the source that provided them also generated 0.1 \(M_\odot\) of Mg and scaling the r-process elements to solar abundances. We find that the implied mass per event for Eu production in most of our stars is \(\gtrsim 10^{-5} \, M_\odot\) and up to \(\approx 10^{-3} \, M_\odot\) of total r-process material. We also find that only a small fraction of first-peak r-process (Sr) production is consistent with a mass per event of \(\lesssim 7.8 \times 10^{-6} \, M_\odot\). However, this result is dependent on our assumption of 0.1 \(M_\odot\) of Mg being ejected in the explosion. For example, a sizable fraction of the stars would become consistent with a mass per event of \(\lesssim 7.8 \times 10^{-6} \, M_\odot\) for a fiducial Mg mass of 0.03 \(M_\odot\).

This implies that standard core-collapse SNe (i.e., those responsible for the majority of Mg production) are not in perfect agreement with being the dominant source of first-peak r-process elements in the early universe, and by extension, that there may be multiple sources of r-process production, consistent with findings by, e.g., Ji et al. (2016c).

4.1. Distinguishing between Rare Events by Environment

This simple analysis lends itself to the mounting evidence that the source(s) of main r-process elements must be rare and yield high masses per event. Today, the two most promising candidates are NSMs (e.g., Lattimer & Schramm 1974; Rosswog et al. 1999; Metzger et al. 2010; Roberts et al. 2011; Barnes & Kasen 2013; Bauswein et al. 2013; Grossman et al. 2014; Ramirez-Ruiz et al. 2015) and jet-driven supernovae (e.g., Winteler et al. 2012; Nishimura et al. 2015), both of which occur at \(\lesssim 1\%\) of the average CCSNe rate and may inject relatively high masses into the ISM per event. Here we focus our efforts on attempting to distinguish between these two scenarios.

While several simulations of NSMs have found the explosion energy to be between \(10^{50–51}\) erg, the maximum energy extractable from a neutron star that gives birth to a magnetar is not as well constrained. Metzger et al. (2015) have found that the birth of a magnetar may be accompanied by an injection of \(10^{52–53}\) erg of energy if the rotational energy is extractable. Figure 6 shows how the constraints implied by our cooling mass argument change by varying the energy of the explosion. While we find that standard CCSNe are incompatible with any reasonable explosion energy, the energy implied by the spin-down of a magnetar in a jet-driven SNe places lower limits on the mass per event of \(\gtrsim 10^{-2} \, M_\odot\). Although the data are not yet able to discern between NSM and rare SNe based on energetics, they demand a high mass per event and a rate much lower than that of typical type II SNe (based on our cooling mass argument), as well as a Mg mass much greater than 0.1 \(M_\odot\) if the Mg is at all coupled to the Eu, as the masses inferred in Figure 5 would be too low to be consistent with a rare event (based on our mixing mass argument).

In addition to the somewhat weak energetic constraints between the two models, we may also consider the possibility that the two mechanisms may take place in different environments. NSMs must be preceded by two SNe, which are highly likely to impart linear momentum to the binary due to a combination of sudden and asymmetric mass loss (e.g., Behroozi et al. 2014). This may result in the binary merging within a shorter timescale (Beniamini et al. 2016a) and in a region far from its birthplace, enriching an environment that is chemically distinct. In contrast, the collapse of a massive star will occur on a timescale of \(\sim 10\) Myr, not allowing the star to migrate far from its birthplace and possibly still within its birth cluster. In particular, if the jet-driven supernovae are some fraction \(f_{\text{SN}}\) of all standard CCSNe, then we expect the local environment to be enriched with the ejecta of \(1/f_{\text{SN}}\) SNe throughout the lifetime of the cluster, assuming a typical cluster dispersal time of a few Myr.

If the ejecta of the standard SNe and jet-driven SN are well mixed, the expected value for the ratio of r-process material to standard α-elements is given by the ratio of their respective production rates. Comparing this mass ratio to solar values, we obtain

\[
[\text{Eu/Mg}]_\text{Sun} \approx -0.7 + \log_{10} \left[ \frac{M_{e,p}^{\text{r-p}}}{M_{\text{Mg,ccsn}}} \right],
\]

Figure 6. Inferred lower limit on r-process ejecta mass based on \(M_{\text{cool}}\) from Section 3. The dashed lines represent the 100% and 50% values for the mass-weighted cumulative histogram as seen in Figure 2. This argument rules out Type II SNe (the purple region denotes the range of current theoretical estimates) as the dominant contributor to the r-process mass budget at low metallicities, and places constraints on the ejecta mass required in scenarios involving magnetars (maroon region).

where \(M_{e,p}^{\text{r-p}}\) and \(M_{\text{Mg,ccsn}}\) are the average r-process and Mg production rates in units of \(10^{-7}\) and \(10^{-3} \, M_\odot\) yr\(^{-1}\), respectively. Note that this is independent of \(f_{\text{SN}}\), as varying the fraction varies both the Eu yield required per event as constrained by \(M_{e,p}\) and the number of accompanying SNe in the same way.
provide a plausible explanation for the carbon-enhanced metal-poor stars (Sluder et al. 2016) as well as the chemical diversity observed in some UFDs (Ji et al. 2016b). In contrast, the uniformity of Mg abundances in low-metallicity halo stars points to efficient mixing occurring after the first SNe. Future observations of abundances in the lowest metallicity stars, in tandem with more detailed hydrodynamical simulations of mixing in the early universe, are needed to shed light on the nature of this discrepancy.

While uncertainties remain in distinguishing these rare events, the assumptions made regarding the cooling mass remain minimal and result in a conservative lower limit regarding the mass of r-process elements synthesized in individual production events. This analysis may lend itself to helping constrain the progenitor(s) of the so-called lighter element primary process (e.g., Travaglio et al. 2004; Montes et al. 2007) by studying abundances of the first- and second-peak r-process elements as well as their star-to-star variations, which will be the topic of future studies.

We thank the anonymous referees, whose suggestions have greatly improved the quality of this manuscript. We thank R. Cooke, R. Foley, D. Kasen, E. Kirby, G. Montes, S. Shen, and M.-R. Wu for insightful discussions and acknowledge financial support from the Packard Foundation, NSF (AST0847563), UCMEXUS (CN-12-578). P.M. gratefully acknowledges support from the NSF Graduate Research Fellowship and the Eugene Cota-Robles Graduate Fellowship.

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**5. Conclusions**

In this paper, we have used simple physical arguments to calculate lower limits on both first-peak and main r-process masses ejected within a single event. We have found, in congruence with other studies, that the implied masses are inconsistent with the rate of typical core-collapse supernovae, and instead are indicative of a rarer event.

Because we only considered single-event candidates, this analysis does not allow us to comment on the trends with metallicity and/or time, which must rely on more detailed galactic chemical evolution (GCE) models. However, we are providing constraints on a critical parameter used in these models, specifically, we provide a minimum yield of Eu per injection event to be used in any GCE model. Our most r-process enhanced star in Figure 2, with a cooling mass of $1.3 \times 10^4 M_\odot$, requires by Equation (2) an Eu yield of $M_{\text{Eu}} > 10^{-6} M_\odot$. This is at least a factor of 30 larger than the Eu yield of $3.7 \times 10^{-8} M_\odot$ used in GCE models that consider CCSNe as the dominant source of Eu in the MW (e.g., Travaglio et al. 2004; Qian & Wasserburg 2007).

By considering the environment in which these rare SNe may take place, we find that the abundances of the α-elements, particularly Mg, are marginally consistent with a fully mixed cloud of the rare SN and corresponding standard CCSNe ejecta, but with significant scatter. This assumes that the ejecta are all well mixed by the time the next generation of stars forms. The extent to which this assumption holds remains unclear, as inhomogeneous mixing of Population III SN ejecta may
