THE UNREASONABLE WEAKNESS OF R-PROCESS COSMIC RAYS IN THE NEUTRON-STAR-MERGER NUCLEOSYNTHESIS SCENARIO

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ABSTRACT

We reach the robust conclusion that, by combining the observed cosmic rays of r-process elements with the fact that the velocity of the neutron-star-merger ejecta is much higher than that of the supernova ejecta, either (1) the reverse shock in the neutron-star-merger ejecta is a very inefficient accelerator that converts less than 0.003% of the ejecta kinetic energy to the cosmic-ray energy or (2) the neutron star merger is not the origin of the Galactic r-process elements. We also find that the acceleration efficiency should be less than 0.1% for the reverse shock of the supernova ejecta with observed cosmic rays lighter than the iron.

Key words: acceleration of particles – cosmic rays – ISM: supernova remnants – nuclear reactions, nucleosynthesis, abundances – shock waves – stars: neutron

1. INTRODUCTION

Where are the r-process elements—neutron-rich, heavy elements such as the gold, platinum, and rare Earth elements—formed in our universe? This is a longstanding problem in nuclear astrophysics (see Arnould et al. 2007; Qian & Wasserburg 2007, for reviews). The r-process nucleosynthesis requires an extremely neutron-rich environment, because the neutrons have to be captured by seed nuclei more rapidly than the β-decay proceeds. Thus, it is widely believed that the r-process nucleosynthesis is intimately related to explosive events involving neutron stars.

The universality of the observed r-process abundance pattern in metal-poor stars suggests that only a single type of astronomical events should be responsible for the nucleosynthesis (Sneden et al. 2008). One possible site is the core-collapse supernova (Burbidge et al. 1957), but theoretical investigations are gathering evidence against the successful r-process nucleosynthesis in this scenario (Qian & Woosley 1996; Wanajo 2013) except for presumably rare magnetorotational supernovae (Nishimura et al. 2015). Another possible site is the merger of binary neutron stars and/or black hole-neutron star binaries, which we collectively call neutron star mergers (Lattimer & Schramm 1974; Symbalisty & Schramm 1982).

The neutron-star-merger scenario seems to be supported by successful r-process nucleosynthesis in nuclear network calculations (Freiburghaus et al. 1999; Wanajo et al. 2014), consistency of the theoretically estimated production rate with the observed abundance (Korobkin et al. 2012), possible detections of the macronova/kilonova following short-hard gamma-ray bursts (Berger et al. 2013; Tanvir et al. 2013; Yang et al. 2015), reproduction of metal-poor r-process-enriched stars in Galactic chemical evolution models (Hirai et al. 2015; Shen et al. 2015; van de Voort et al. 2015), and indication of a “low-rate/high-yield” event from the deep-sea plutonium measurement (Hotokezaka et al. 2015) and from the observation of ultrafaint dwarf galaxies (Ji et al. 2016).

In this paper, we revisit an old idea that the composition measurement of cosmic rays could serve as a tool to explore the origin of elements (see, e.g., Arnett & Schramm 1973), aiming at critically assessing the plausibility of the neutron-star-merger scenario for the r-process nucleosynthesis. Because the long-term evolution of the neutron-star-merger ejecta should resemble that of the supernova ejecta, i.e., supernova remnants (Nakar & Piran 2011), cosmic rays should be accelerated at the shock associated with the blast-wave interaction between the ejecta and interstellar medium (Kyutoku et al. 2013; Takami et al. 2014a). If the ejecta from any event contain r-process elements, they could be accelerated when the reverse shock sweeps into the ejecta, and the amount of accelerated r-process elements (hereafter, r-process cosmic rays) should depend on the ejecta properties such as the mass and velocity. This suggests that the flux of r-process cosmic rays could enable us to distinguish the nucleosynthesis sites, namely the supernova or the neutron star merger.

Our finding is summarized as follows. First, the flux of r-process cosmic rays around the energy of 1 GeV nucleon$^{-1}$ could be enhanced by a few orders of magnitude compared to the flux expected from the supernova forward shock with the solar composition, if the r-process elements are synthesized in the neutron star merger. By contrast, the r-process cosmic-ray flux should not be significantly enhanced if the supernova is the nucleosynthesis site. The reason for this difference is the high velocity of the neutron-star-merger ejecta, which can increase the total energy of the r-process cosmic rays for a given mass of r-process elements. Second, the observed cosmic rays do not show selective enhancement of r-process elements and are known to be consistent with the solar abundance at the acceleration sites (Ellison et al. 1997; Meyer et al. 1997). The weak flux of r-process cosmic rays indicates that either (1) the particle acceleration is very inefficient at the reverse shock in the r-process-dominated neutron-star-merger ejecta or (2) the neutron star merger does not contribute to Galactic r-process elements significantly.

2. IMPORTANT QUANTITIES

Before starting the discussion of r-process cosmic rays, we list important quantities used in later estimation. The relative mass fraction of r-process elements in the solar neighborhood
is estimated to be (Qian 2000)
\[ \dot{X} \sim 10^{-7}. \] (1)
This implies that the amount of r-process elements in our Galaxy is \( M_r \sim 10^4 M_\odot \) and that the Galactic r-process element production rate is \( \dot{M}_r \sim 10^{-6} M_\odot \text{ yr}^{-1} \). This quantity will play a key role in our estimation to alleviate uncertainties associated with the event rate, ejecta mass, and r-process yield per event.

The amount of r-process elements synthesized in a single event under a hypothetical production scenario is estimated by dividing the Galactic production rate, \( \dot{M}_r \), by the event rate. On one hand, the Galactic supernova rate is estimated to be \( \dot{R}_{SN} \sim 3 \times 10^{-2} \text{ yr}^{-1} \) (see, e.g., Qian 2000). Thus, the single-event yield of r-process elements should be \( M_{r,SN} = \dot{M}_r/\dot{R}_{SN} \sim 3 \times 10^{-5} M_\odot \) if the supernova is the production site. This value should be compared with the typical mass of the supernova ejecta, \( M_{ej,SN} \sim 3 M_\odot \) (see, e.g., Truelove & McKee 1999), and therefore the fraction of r-process elements is
\[ X_{r,SN} \sim 10^{-5}. \] (2)
On the other hand, the Galactic neutron-star-merger rate is estimated to be \( \dot{R}_{NSM} \sim 10^{-4} \text{ yr}^{-1} \) with a large uncertainty (Abadie et al. 2010). This gives us an estimate of the single-event yield as \( M_{r,NSM} = \dot{M}_r/\dot{R}_{NSM} \sim 0.01 M_\odot \) for the neutron-star-merger scenario. Assuming that all the ejecta material is synthesized to r-process elements (Freiburghaus et al. 1999; Wanajo et al. 2014), i.e.,
\[ X_{r,NSM} \sim 1, \] (3)
this value is consistent with the typical ejecta mass \( M_{ej,NSM} \sim 0.01 M_\odot \) obtained by general-relativistic hydrodynamical simulations (Bauswein et al. 2013; Hotokezaka et al. 2013a) and is also roughly sufficient to power a possible macronova/kilonova associated with GRB 130603B (Berger et al. 2013; Hotokezaka et al. 2013b; Tanvir et al. 2013; but see also Kisaka et al. 2015).

It is widely accepted that Galactic cosmic rays are accelerated from the inter/circumstellar material at the forward shock of blast waves associated with the supernova ejecta, whereas the acceleration mechanism is not fully understood yet. This scenario requires a fraction
\[ \epsilon_{CR} \sim 0.1 \] (4)
of the ejecta kinetic energy to be converted to the cosmic-ray energy. We use the fiducial value, \( \epsilon_{CR} \sim 0.1 \), for both the supernova and neutron-star-merger forward shocks in this study. It should be cautioned that the neutron-star-merger remnants could be different from the supernova remnants in the nonspherical geometry and in the circumburst medium that is not affected by winds or precursors (Montes et al. 2016).

The most uncertain quantity is the fraction of the energy given to cosmic rays at the reverse shock to that at the forward shock, \( \eta_{rf} \). This fraction is crucial for the total energy of the r-process cosmic rays, because they are expected to be accelerated not only at the forward shock but also at the reverse shock sweeping into the ejecta. We take a provisional value of this fraction to be
\[ \eta_{rf} \sim 0.01 \] (5)
for both the supernova and neutron-star-merger ejecta, because this is an upper limit derived by the condition that the reverse-shock acceleration does not dominate the forward-shock acceleration for the elements synthesized in the supernova (see the next section). The discussion on the r-process cosmic rays will impose a tighter constraint on the acceleration efficiency at the reverse shock, \( \epsilon_{CR,r} \equiv \eta_{rf} \epsilon_{CR} \), in the neutron-star-merger scenario.

Before closing this section, we caution that both \( \epsilon_{CR} \) and \( \eta_{rf} \) can be different between the supernova ejecta and the neutron-star-merger ejecta. In the next section, we tentatively take common values for them to estimate r-process cosmic rays in the neutron-star-merger nucleosynthesis scenario. After that, we derive constraints on these parameters separately for the supernova and the neutron star merger.

3. R-PROCESS COSMIC RAYS

We focus on the flux at the lowest energy range for r-process cosmic rays, \( \sim 1 \text{ GeV} \text{ nucleon}^{-1} \). In this range, the flux is determined primarily by the total energy or injection rate of r-process cosmic rays irrespective of the spectral index, the prediction of which requires the precise knowledge of acceleration, escape, and propagation. The Galactic confinement time does not affect comparisons among different acceleration sites, because it should be determined solely by the rigidity. Although the composition changes moderately during the Galactic propagation, this again does not affect the comparisons.

First, we estimate the energy injection rate of r-process cosmic rays out of the inter/circumstellar material at the forward shock associated with the supernova ejecta. Taking the typical kinetic energy of the supernova ejecta to be \( \dot{E}_{ej,SN} \sim 10^{51} \text{ erg} \) (see, e.g., Truelove & McKee 1999), the energy injection rate of cosmic rays is estimated to be \( \dot{E}_{CR} = \epsilon_{CR} \dot{E}_{ej,SN} \dot{R}_{SN} \sim 3 \times 10^{48} \text{ erg yr}^{-1} \). This amount roughly matches the total generation rate of Galactic cosmic rays estimated from the observation. If we assume that the cosmic-ray composition ratio is proportional to the elemental abundance, the energy injection rate of r-process cosmic rays is given by
\[ \dot{E}_{r,ISM} = X_r \dot{E}_{CR} \sim 3 \times 10^{41} \text{ erg yr}^{-1}. \] (6)
We consider the enhancement of refractory and/or large-mass-number elements (Ellison et al. 1997; Meyer et al. 1997) separately in the next section. The contribution from the forward shock associated with the neutron-star-merger ejecta is negligible due to the low event rate.

Next, we estimate the energy injection rate of r-process cosmic rays for the supernova nucleosynthesis scenario. The energy injection rate of all the accelerated particles at the reverse shock is given by
\[ \eta_{rf} \dot{E}_{CR} \sim 3 \times 10^{46} \text{ erg yr}^{-1} (\eta_{rf}/0.01). \] (7)
Taking \( X_{r,SN} \sim 10^{-5} \), we obtain
\[ \dot{E}_{r,SN} = X_{r,SN} \eta_{rf} \dot{E}_{CR} \]
\[ = X_{r,SN} \eta_{rf} \epsilon_{CR} \dot{E}_{ej,SN} \dot{R}_{SN} \]
\[ \sim 3 \times 10^{41} \text{ erg yr}^{-1} (\eta_{rf}/0.01), \] (7)
again assuming that the cosmic-ray composition is given by the relative mass fraction. Thus, if the supernova is the r-process
nucleosynthesis site, we do not expect significant enhancement of r-process cosmic rays compared to those from the inter/circumstellar material, $\dot{E}_{r, \text{ISM}}$, as far as $\eta_{r,ff} \lesssim 0.01$.

Finally, we estimate the energy injection rate of r-process cosmic rays for the neutron-star-merger nucleosynthesis scenario. We take the ejecta kinetic energy to be a typical value derived by general-relativistic simulations of binary neutron star mergers, $E_{\text{ej, NSM}} \sim 3 \times 10^{50}$ erg (Bauswein et al. 2013; Hotokezaka et al. 2013a), which corresponds to the ejecta velocity $v_{\text{ej, NSM}} \sim 0.2 c$ with $c$ as the speed of light. Using this value, the energy injection rate of r-process cosmic rays is given by

$$\dot{E}_{r, \text{NSM}} = X_{r, \text{NSM}} \eta_{r,ff} \dot{E}_{\text{ej, NSM}} R_{\text{NSM}}$$

$$\sim 3 \times 10^{43} \text{ erg yr}^{-1} \left( \frac{\eta_{r,ff}}{0.01} \right),$$

for our fiducial $c_{\text{CR}} \sim 0.1$.

To summarize, we obtain the ratios

$$\dot{E}_{r, \text{NSM}} \sim 100 \dot{E}_{r, \text{SN}} \sim 100 \left( \frac{\eta_{r,ff}}{0.01} \right) \dot{E}_{r, \text{ISM}},$$

if we adopt the same values of $c_{\text{CR}}$ and $\eta_{r,ff}$ for both scenarios. This suggests that the flux of r-process cosmic rays at $\sim 1 \text{ GeV nucleon}^{-1}$ could be enhanced by a few orders of magnitude compared to the expectation from the supernova forward shock with the solar composition if the r-process nucleosynthesis occurs in the neutron star merger, while the enhancement is not expected in the supernova scenario. Note that the relation $\dot{E}_{r, \text{SN}} \sim (\eta_{r,ff}/0.01) \dot{E}_{r, \text{ISM}}$ also holds for any lighter-than-iron product X of the supernova nucleosynthesis, so that the upper limit on the acceleration efficiency from the supernova nucleosynthesis is $\eta_{r,ff} \lesssim 0.01$. Otherwise, the cosmic-ray composition below the iron could have changed substantially from the solar composition (beyond the spallation modification).

The enormous enhancement for the neutron-star-merger scenario, despite the same total r-process yields as the supernova scenario, is ascribed to the high ejecta velocity. To put it simply, the energy injection rate of r-process cosmic rays at the reverse shock is given by

$$\dot{E}_{r,*} = \eta_{r,ff} \dot{E}_{r, \text{ISM}} v_{r, *}^2 / 2,$$

where $\ast$ stands for either SN or NSM, and thus the energy injection rate at the reverse shock is proportional to the squared ejecta velocity $v_{\text{ej, NSM}}^2$, which is larger by $\sim 100$ for the neutron star merger than for the supernova. This ratio is completely free from uncertainties associated with $X_{r,ss}$, $M_{\text{ej,ss}}$, and $R_s$. The value of $v_{\text{ej, NSM}}^2$ may span a range of $0.01-0.1c^2$ (Bauswein et al. 2013; Hotokezaka et al. 2013a), and therefore its uncertainty may be much smaller than those of the event rate and ejecta mass.

The above discussions are applicable even if the r-process elements are produced by rare events like the magnetorotational supernova (e.g., Nishimura et al. 2015). Given that the ejecta mass and energy are comparable to the normal supernova, the ejecta velocity is similar to $v_{\text{ej, SN}}$, so that Equations (9) and (10) remain valid.

### 4. WEAKNESS THEREOF

The observations of heavy cosmic rays can be explained solely by the forward shock of supernova blast waves without invoking any contribution from the reverse shock (Binns et al. 1989; Westphal et al. 1998; Donnelly et al. 2012). They find (1) similar enhancement by a factor of 20–30 for iron-group and refractory r/s-process cosmic rays and (2) enhancement by a factor of 3–10 for volatile r/s-process cosmic rays. It is also found that the enhancement ratio may be correlated with the mass number of elements (Rauch et al. 2009). It has to be cautioned that the measured elements are only classified by the charge, and the isotope ratios are not accurately measured. This precludes the clear distinction between r-process and s-process elements. However, no systematic difference in enhancement is found between r-process-dominant elements such as the platinum and s-process-dominant elements such as the cerium (see, e.g., Table 1 of Sneden et al. 2008, for the breakdown), and thus the enhancement is likely to be similar for both elements. The strong enhancement of the refractory elements is explained by efficient acceleration via suprathermal injection from dust grains (Ellison et al. 1997; Meyer et al. 1997; Rauch et al. 2009). Furthermore, the enhancement of s-process cosmic rays is explained by neither the supernova nor neutron-star-merger ejecta, because the ejecta are hardly expected to be enriched by s-process elements.

The observations do not support Equation (9) with $\eta_{r,ff} \sim 0.01$, i.e., the selective r-process enhancement in heavy cosmic rays. This indicates the weakness of r-process cosmic rays from the neutron star merger. The contribution from the neutron-star-merger ejecta to the enhancement should be less than a factor of three, i.e., $\dot{E}_{r, \text{NSM}} \lesssim 3 \dot{E}_{r, \text{ISM}}$; otherwise, it contradicts the observations of refractory elements such as the zirconium relative to the iron and with the observations of volatile elements such as the krypton (Ellison et al. 1997; Meyer et al. 1997).
The weakness or even absence of enhanced r-process cosmic rays places a constraint on particle acceleration at the reverse shock of blast waves associated with the neutron-star-merger ejecta. Figure 1 shows the allowed acceleration efficiency of r-process cosmic rays at the reverse shock in the neutron-star-merger nucleosynthesis scenario. This figure indicates that, if the neutron-star-merger scenario is true, the reverse shock associated with the r-process-dominated ejecta has to be an inefficient accelerator with

\[ \epsilon_{r,ff} = \eta_{r,ff} \epsilon_{CR} \lesssim 0.003\%. \] (11)

This constraint is more severe by a factor of \( \sim 100/3 \sim 30 \) than that obtained from the observed cosmic rays of supernova nucleosynthesis products, \( \eta_{r,ff} \lesssim 0.1\% \), and could serve as important information for the physics of particle acceleration.

How unreasonable this low acceleration efficiency is depends on the difference between the supernova and the neutron star merger. We could assume that the cosmic-ray energy is distributed according to the mass processed by the shock to argue that the low efficiency is a reasonable outcome of the high-velocity ejecta. Assuming that the particle acceleration becomes inefficient at the time when the blast-wave velocity decreases to a fixed value of \( v_{\text{sh}} \sim 100 \text{ km s}^{-1} \), at which the radiative cooling sets in, the mass swept by the forward shock before the termination of acceleration \( M_{\text{e,}\ast} \) is expected to be proportional to \( E_{ej,\ast} \) due to the relation \( E_{ej,\ast} \propto M_{\ast} v_{\text{sh}}^2 \) in the Sedov–Taylor phase. Thus, using \( E_{sj,\ast} = M_{\ast} v_{\text{sh}}^2 / 2 \), we could expect \( \eta_{r,ff} \sim M_{\ast}/M_{ej,\ast} \propto E_{ej,\ast}/E_{sj,\ast} \propto v_{\text{sh}}^{-2} \). This possibility naturally explains the two-orders-of-magnitude-lower efficiency of the neutron-star-merger scenario, and moreover, predicts \( \eta_{r,ff} \sim 10^{-3} \) for the supernova and \( \sim 10^{-5} \) for the neutron star merger satisfying observational constraints. By contrast, we could also assume that the cosmic-ray energy is distributed according to the energy processed by the shock to argue that the low efficiency is unreasonable. In this case, the cosmic-ray energy increases in a self-similar manner during the Sedov–Taylor phase as \( E_{CR} \propto 1/t \) in accordance with the self-similar hydrodynamic evolution (see also Bell 2015). Thus, we could expect moderate dependence on the ejecta velocity as \( \eta_{r,ff} \propto \ln t \propto \ln(1/v_{\text{sh}}) \), and this predicts that the efficiency varies at most only by a factor of two to three between the supernova and the neutron star merger with \( \eta_{r,ff} \sim 0.01 \) for both cases.

It is worthwhile to consider other reasons for the inefficiency of the reverse-shock acceleration in the neutron star merger. They may include weak magnetic fields in the ejecta, absence of r-process dust grains, and/or energy loss to the adiabatic expansion. The absence of r-process dust grains in the neutron-star-merger ejecta is consistent with the finding of Takami et al. (2014b), although this effect is not sufficient to fully account for the weakness. Conversely, if the reverse shock turns out to be a moderately efficient accelerator for the neutron-star-merger ejecta, our result implies that the neutron star merger contributes very little or not at all to the Galactic r-process enrichment.

5. FUTURE PROSPECT

Precise measurement of the cosmic-ray composition is useful to narrow down the uncertainty range. In particular, a detailed investigation of the difference between r-process and s-process cosmic-ray fluxes is highly appreciated, because the contribution from any ejecta is likely to be much larger in the r-process enhancement than in the s-process enhancement. Moreover, uncertainties should be reduced if we compare elements with similar mass numbers and similar volatility. For this purpose, it is important to measure the isotope ratio of heavy cosmic rays to precisely separate r-process and s-process elements. We also have to understand nuclear interactions like spallation during the cosmic-ray propagation to precisely recover the composition at the acceleration site from the observed one.

The velocity of the neutron-star-merger ejecta also requires an investigation. While it is safely expected that the ejecta velocity is higher for the neutron star merger than for the supernova, the precise value depends on the mass ejection mechanism. For example, the velocity is likely to become low if the late-time activity such as disk winds contributes substantially to the mass ejection (Fernández & Metzger 2013; Just et al. 2015; Kiuchi et al. 2015). The velocity could be determined by observing synchrotron emission around the Sedov time (Nakar & Piran 2011; Takami et al. 2014a).

It is very difficult to pin down the acceleration efficiency at the reverse shock accurately, while this is one of the last pieces to assess the plausibility of the neutron-star-merger scenario for the r-process nucleosynthesis by studying cosmic rays. We could in principle infer the efficiency by observing reverse-shock emission, such as gamma-rays from hadronic interaction (see, e.g., Helder & Vink 2008, for leptonic emission from Cas A). However, the large distance of \( \sim 100 \text{ Mpc} \) expected for a yearly neutron-star-merger event prohibits us from taking this approach in real life (Abadie et al. 2010).

Theoretical investigations of the reverse-shock acceleration are highly desired, particularly for the r-process-dominated ejecta. Relevant topics include magnetic-field amplification from the value typical of neutron stars, injection of r-process elements involving possible dust formation, and energy loss to the adiabatic expansion before the escape. If efficient acceleration at the reverse shock would be a likely outcome, the unreasonable weakness of r-process cosmic rays challenges the neutron-star-merger nucleosynthesis scenario.

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