ENRICHMENT OF \( r \)-PROCESS ELEMENTS IN DWARF SPHEROIDAL GALAXIES IN CHEMO-DYNAMICAL EVOLUTION MODEL

YUTAKA HIRAI\textsuperscript{1,2,7}, YUHRI ISHIMARU\textsuperscript{3,4}, TAKAYUKI R. SAITO\textsuperscript{5}, MICHIKO S. FUJI\textsuperscript{5}, JUN HIDAKA\textsuperscript{2,6}, AND TOSHIKAZU KAJINO\textsuperscript{1,2}

\textsuperscript{1} Department of Astronomy, Graduate School of Science, the University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan; yutaka.hirai@nao.ac.jp
\textsuperscript{2} Division of Theoretical Astronomy, National Astronomical Observatory of Japan, 2-21-1 Osawa Mitaka, Tokyo 181-8588, Japan
\textsuperscript{3} Department of Material Science, International Christian University, 3-10-2 Osawa, Mitaka, Tokyo 181-8585, Japan
\textsuperscript{4} Institut d’Astrophysique de Paris, 98bis Boulevard Arago, F-75014, Paris, France
\textsuperscript{5} Earth-Life Science Institute, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan
\textsuperscript{6} School of Science and Engineering, Meisei University, 2-1-1 Hodokubo, Hino, Tokyo 191-0042, Japan

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ABSTRACT

The rapid neutron-capture process (\( r \)-process) is a major process for the synthesis of elements heavier than iron-peak elements, but the astrophysical site(s) of the \( r \)-process has not yet been identified. Neutron star mergers (NSMs) are suggested to be a major \( r \)-process site according to nucleosynthesis studies. Previous chemical evolution studies, however, required unlikely short merger times of NSMs to reproduce the observed large star-to-star scatters in the abundance ratios of \( r \)-process elements to iron: the [Eu/Fe] of extremely metal-poor stars in the Milky Way (MW) halo. This problem can be solved by considering chemical evolution in dwarf spheroidal galaxies (dSphs), which would be building blocks of the MW and have lower star formation efficiencies than the MW halo. We demonstrate the enrichment of \( r \)-process elements in dSphs by NSMs using an \( N \)-body/smoothed particle hydrodynamics code. Our high-resolution model reproduces the observed [Eu/Fe] due to NSMs with a merger time of 100 Myr when the effect of metal mixing is taken into account. This is because metallicity is not correlated with time \( \sim \)300 Myr from the start of the simulation due to the low star formation efficiency in dSphs. We also confirm that this model is consistent with observed properties of dSphs such as radial profiles and metallicity distribution. The merger time and the Galactic rate of NSMs are suggested to be \( <\sim \)300 Myr and \( \sim \)10\(^{-4}\) year\(^{-1}\), respectively, which are consistent with the values suggested by population synthesis and nucleosynthesis studies. This study supports the argument that NSMs are the major astrophysical site of the \( r \)-process.

Key words: galaxies: abundances – galaxies: dwarf – galaxies: evolution – Local Group – methods: numerical

1. INTRODUCTION

Elements heavier than those of the iron-peak are mainly synthesized by the rapid neutron capture process (\( r \)-process) as well as the \( s \)- and \( p \)-processes. More than 90\% of elements such as europium (Eu), gold (Au), and platinum (Pt)\textsuperscript{7} in the solar system are synthesized by the \( r \)-process (Burris et al. 2000). A sufficiently neutron-rich environment is required in order to synthesize \( r \)-process elements with a mass number (\( A \)) of over 110.

The observed \( r \)-process elemental abundance ratios, such as [Eu/Fe],\textsuperscript{8} in extremely metal-poor (EMP) stars ([Fe/H] \( \ll -3 \)) show large star-to-star scatters. These scatters are seen in EMP stars in the Milky Way (MW) halo as well as Local Group (LG) dwarf spheroidal galaxies (dSphs; e.g., McWilliam et al. 1995; Woolf et al. 1995; Ryan et al. 1996; Shetrone 1996; McWilliam 1998; Burris et al. 2000; Fulbright 2000; Westin et al. 2000; Norris et al. 2001; Johnson 2002; François et al. 2003, 2007; Honda et al. 2004; Sneden et al. 2008; Tolstoy et al. 2009; Frebel et al. 2010a, 2010b; Letarte et al. 2010; Ishigaki et al. 2013). This result clearly indicates that \( r \)-process elements are not synthesized in all kinds of stars.

Proto-neutron star (PNS) winds of core-collapse supernovae (CCSNe) have long been regarded as one of the possible sites of the \( r \)-process (e.g., Meyer et al. 1992; Woosley et al. 1994).

Previous chemical evolution studies have suggested that the observed [Eu/Fe] scatter is well reproduced by models assuming that CCSNe of low-mass (8–10\( M_\odot \)) progenitors produce \( r \)-process elements (e.g., Mathews et al. 1992; Ishimaru & Wanajo 1999; Travaglio et al. 1999, 2001; Tsujimoto et al. 2000; Ishimaru et al. 2004; Argast et al. 2004). However, recent hydrodynamical simulations of CCSNe, which include neutrino transport in a sophisticated manner, suggest that the PNS winds of CCSNe do not necessarily produce the neutron-rich condition suitable for the \( r \)-process (e.g., Reddy et al. 1998; Roberts 2012; Martínez-Pinedo et al. 2012; Roberts et al. 2012; Horowitz et al. 2012). Nucleosynthesis calculations suggest that heavy elements with \( A \geq 110 \) are difficult to synthesize in CCSNe due to such neutron-rich environments which are too weak (e.g., Wanajo et al. 2011; Wanajo 2013).

Binary neutron star mergers (NSMs) are also suggested as a promising site of the \( r \)-process (Lattimer & Schramm 1974, 1976; Lattimer et al. 1977; Symbalisty & Schramm 1982; Eichler et al. 1989; Meyer 1989). Recent detailed nucleosynthesis calculations show that heavy \( r \)-process elements are successfully synthesized in NSMs (Freiburghaus et al. 1999; Goriely et al. 2011; Korobkin et al. 2012; Bauswein et al. 2013; Rosswog et al. 2012; Roberts et al. 2012; Horowitz et al. 2012). In addition, the near-infrared afterglow of the \textit{Swift} short gamma-ray burst GRB 130603B (Berger et al. 2013; Tanvir et al. 2013) was detected. This is evidence that the progenitors of short gamma-ray bursts are compact binary mergers and that \( r \)-process nucleosynthesis occurs there (Tanaka & Hotokezaka 2013).
NSMs have long merger times and low rates. Neutron star (NS) binaries lose their energy very slowly due to gravitational emissions. The merger time is estimated to be \( \gtrsim 100 \) Myr based on observed binary pulsars (Lorimer 2008). Recent predictions from population synthesis models also suggest that most NS binaries merge \( \gtrsim 100 \) Myr after their formation (Dominik et al. 2012). On the other hand, the NSM rate is estimated from observed binary pulsars \( (10^{-6} \sim 10^{-3} \text{year}^{-1}) \) for a MW size galaxy; Abadie et al. 2010a).

However, early studies of galactic chemical evolution pointed out that it is difficult to reproduce the observed trend of \([\text{Eu}/\text{Fe}]\) for EMP stars by NSMs due to their long merger time and low rate (Mathews & Cowan 1990; Argast et al. 2004). Most other recent studies also conclude that a short merger time \((\lesssim 10 \text{Myr})\) or a second \(r\)-process site is required to account for the large star-to-star scatter in EMP stars (Komiya et al. 2014; Matteucci et al. 2014; Tsujimoto & Shigeyama 2014; Cescutti et al. 2015; Wehmeyer et al. 2015). On the other hand, detailed population synthesis calculations suggest that the production of NSMs with short-merger times \((\sim 10 \text{Myr})\) highly depends on the treatment of the common envelope phase which is not well understood (e.g., Portegies Zwart & Yungelson 1998; Dominik et al. 2012; Kinugawa et al. 2014). Dominik et al. (2012) suggest that NSMs with merger times of \(\lesssim 10 \text{Myr}\) cannot be produced in their most pessimistic model assuming that each common envelope with a Hertzsprung gap donor causes a merger (Submodel B in Dominik et al. 2012). In addition, so far there is no observational evidence that binary pulsars which merge within \(\sim 10 \text{Myr}\) exist (Lorimer 2008).

This discrepancy may be resolved if the Galactic halo is formed via mergers of sub-halos within a hierarchical structure formation framework (Ishimaru et al. 2015). Ishimaru et al. (2015) calculate the enrichment of \(r\)-process elements by NSMs with merger times of 100 Myr (95% of NSMs) and 1 Myr (5% of NSMs) in their one-zone chemical evolution model for each sub-halo. They suggest that \([\text{Eu}/\text{Fe}]\) increases at \([\text{Fe/H}] \lesssim -3\) if the star formation efficiencies are lower in less massive sub-halos. According to their calculations, the observed scatters in \([\text{Eu}/\text{Fe}]\) in metal-poor stars could possibly be explained by NSMs with merger times of 100 Myr. Key factors of chemical evolution such as the time variation of the star formation rate \((\text{SFR})\), outflow, and inflow strongly depend on thermodynamical feedback from supernovae \((\text{SNe})\). Detailed chemo-dynamical evolution studies in low-mass galaxies such as sub-halos are highly desirable to justify their assumptions in describing the enrichment history of \(r\)-process elements in a self-consistent manner between the dynamical and chemical evolution of galaxies.

Recent hydrodynamical studies performed a series of simulations of galaxy formation assuming that NSMs are a major site of the \(r\)-process (Shen et al. 2015; van de Voort et al. 2015). van de Voort et al. (2015) suggest that gas mixing processes such as galactic winds and hydrodynamic flows play important roles in explaining the observed Galactic \(r\)-process ratio. Their high-resolution model with \(7.1 \times 10^4 \text{M}_\odot\) for the mass of one gas particle \((m_{\text{gas}})\), however, has difficulty reproducing the observed \(r\)-process abundance ratios. They imply that additional metal mixing is required to explain the observation. Shen et al. (2015) also suggest that the observed \(r\)-process abundance ratios could be taken into account in their NSM models if metal mixing in the star-forming (SF) region is implemented. However, the mass resolution \((m_{\text{gas}} = 2.0 \times 10^3 \text{M}_\odot)\) in their models is as low as that in the fiducial low-resolution model of van de Voort et al. (2015; \(m_{\text{gas}} = 5.7 \times 10^4 \text{M}_\odot\)). It is therefore important to demonstrate whether or not NSM models can account for the observations with independent simulations of much higher resolution.

In this paper, we calculate the enrichment of \(r\)-process elements ejected by NSMs in low-mass galaxies with high-resolution \((m_{\text{gas}} = 4.0 \times 10^2 \text{M}_\odot)\) chemo-dynamical evolution models. We perform \(N\)-body/smoothed particle hydrodynamics (SPH) simulations of \(d\)SPh models using the ASURA code (Saitoh et al. 2008, 2009). We discuss the effects of metal mixing in star-forming region as well as the dependence on SFR, merger time, and the rate of NSMs.

In Section 2, we introduce our code and models. In Section 3, we compare the model predictions and observed properties of \(d\)SPhs generated by our models. In Section 4, we discuss the enrichment of \(r\)-process elements in \(d\)SPhs. Finally, in Section 5, we summarize our main results.

2. METHOD AND MODELS

2.1. N-Body/SPH Code, ASURA

We perform a series of simulations using the \(N\)-body/SPH code ASURA (Saitoh et al. 2008, 2009). We adopt three different kinds of particles in our simulations: dark matter, gas, and star particles. We treat dark matter and star particles as collisionless. Dark matter particles contribute to the dynamical evolution of our model galaxies. Star particles mainly contribute to the feedback of energy and the heavy elements produced by CCSNe. We solve the hydrodynamical evolution of gas particles using SPH (e.g., Gingold & Monaghan 1977; Lucy 1977; Monaghan & Lattanzio 1985; Monaghan 1992).

Here, we describe the implementation of gravity and hydrodynamics in ASURA. Gravity is calculated using a treecode (Barnes & Hut 1986) with the GRAPE method (Makino 1991) and the Phantom-GRAPE library (Tanikawa et al. 2012). Hydrodynamics is computed using a standard SPH method. For the integration of a self-gravitating fluid system, we adopt the fully asynchronous split time-integrator algorithm in order to reduce the calculation cost (Saitoh & Makino 2010). We use the time-step limiter, which forces the timestep difference among neighboring particles to be less than four times long, in order to follow the evolution of strong shock regions such as SN remnants (Saitoh & Makino 2009). We use a metallicity dependent cooling/heating function generated by Cloudy (Ferland et al. 1998, 2013). The cooling/heating function covers the temperature range from \(10^4\) to \(10^8\) K.

We allow star formation when a gas particle satisfies three conditions: (1) the particle is collapsing \((\nabla \cdot v < 0)\), (2) the density is higher than the threshold density, \(n_{\text{th}}\), (3) the temperature is lower than the threshold temperature, \(T_{\text{th}}\) (e.g., Navarro & White 1993; Katz et al. 1996; Stinson et al. 2006). We adopt \(n_{\text{th}} = 100 \text{cm}^{-3}\) for our fiducial model, which is the mean density of giant molecular clouds \((\text{GMCs})\). We adopt \(T_{\text{th}} = 1000\) K for our fiducial model. The value of \(T_{\text{th}}\) is insensitive to the final structure of the galaxies (Saitoh et al. 2008).

When a gas particle satisfies the three conditions above, it becomes eligible to form new collisionless star particles. Star particles are produced with the following probability according
where \( m_* \) and \( m_{\text{gas}} \) are the masses of star and gas particles, respectively, and \( c_* \) is the dimensionless star formation efficiency (SFE) parameter. We set \( m_* = m_{\text{gas}}/3 \) following Okamoto et al. (2003, 2005). The mass of a gas particle in our fiducial model is initially assumed to be \( 4.0 \times 10^2 M_{\odot} \), but it is reduced by star formation. When the mass of a gas particle becomes lower than one-third of its initial mass, then the particle is converted into a collisionless particle. The dimensionless SFE parameter of our fiducial model (\( c_* = 0.033 \)) is chosen based on the slow star formation model (Zuckerman & Evans 1974; Krumholz & Tan 2007). Saitoh et al. (2008) suggest that when \( n_{\text{th}} = 100 \text{ cm}^{-3} \) is adopted, the final results are fairly insensitive to the adopted value of \( c_* \), in their MW model. In the Appendix, we also confirm this result in our dSph models. Each star particle is treated as a single stellar population, i.e., each star particle is assumed to be an assembly of stars with the same age and the same metallicity. The initial mass function (IMF) of star particles is the Salpeter IMF: \( \phi = m^{-x} \), where \( x = 1.35 \) (Salpeter 1955) with a mass range of \( 0.1 \leq M_{\odot} \leq 40 M_{\odot} \). In this model, stars more massive than \( 40 M_{\odot} \) end their life as black holes. Star particles, which explode in a time interval of \( \Delta t \), are selected by the following probability (\( P_{\text{CCSNe}} \)):

\[
P_{\text{CCSNe}} = \frac{\int_{m(t)}^{m(t+\Delta t)} \phi(m') m'^{x-1} dm'}{\int_{m(t)}^{m(t+\Delta t)} \phi(m') m^{x-1} dm'},
\]

where \( m(t) \) is the turn off mass at age \( t \). Each CCSN explosion distributes \( 10^{51} \text{ erg} \) of thermal energy to the surrounding SPH particles. The mass of one star particle is \( \sim 100 M_{\odot} \). When a particle explode as CCSNe, the number of CCSNe inside each star particle corresponds to \( \sim 1 \). This method is also adopted in other studies (e.g., Okamoto et al. 2008; Saitoh et al. 2008). In addition to the SN feedback, we implement heating by an \( H_2 \) region formed around young stars. The number of Ly\(\alpha \) photons is evaluated using PEGASE (Fioc & Rocca-Volmerange 1997). The parameters of these baryonic physics are listed in Table 1.

### Table 1

Parameters of Baryon Physics

| Quantity                              | Symbol | Fiducial values\(^a\) | Variation       |
|---------------------------------------|--------|-----------------------|-----------------|
| Dimensionless SFE parameter           | \( c_* \) | 0.033                 | 0.033, 0.5      |
| Threshold density for star formation  | \( n_{\text{th}} \) | 100 cm\(^{-3}\)      | 0.1–100 cm\(^{-3}\) |
| Threshold temperature for star formation | \( T_{\text{th}} \) | \( 1 \times 10^3 \text{ K} \) | \( 1 \times 10^3\)–\(3 \times 10^4 \text{ K} \) |
| SN explosion energy                   | \( \epsilon_{\text{SN}} \) | \( 1 \times 10^3 \text{ erg} \) | \( (0.03–1) \times 10^3 \text{ erg} \) |

Note.

\(^a\) Fiducial values of \( c_*, n_{\text{th}}, T_{\text{th}}, \epsilon_{\text{SN}} \) are taken from Saitoh et al. (2008).

2.2. Chemical Enrichment Process

We take into account both CCSNe and NSMs in our models. We set the initial gas metallicity equal to zero. CCSNe produce Fe and NSMs produce Eu, which is regarded as a representative element of the \( r \)-process. Binary black hole-NSMs are also expected to eject \( r \)-process elements (e.g., Korobkin et al. 2012; Mennekens & Venbeveren 2014). However, they affect the rate of production of \( r \)-process elements due to several factors, which are much smaller than the uncertainty of the rate of NSMs. We therefore only implement NSMs for simplicity. We assume that gas particles around a star particle are enriched with metals when a CCSN or NSM occurs in a star particle. Metals are distributed over 32 nearest neighbor particles using the weights of the SPH kernel. The mass of an element \( X \) in the \( j \)-th neighbor particle ejected by the \( i \)-th star particle, \( \Delta M_{X,j} \), is given by

\[
\Delta M_{X,j} = \frac{m_j}{\rho_j} M_{X,i} W(r_{ij}, h_{ij}),
\]

where \( r_{ij} \) is the distance between particles \( i \) and \( j \), \( h_{ij} \) is the smoothing length, and \( W(r_{ij}, h_{ij}) \) is the SPH kernel given by a cubic spline function (e.g., Kawata 2001), and the density of the gas particles is given as

\[
\rho_i = \sum_{i \neq j} m_j W(r_{ij}, h_{ij}).
\]

The scope of this paper allow us to discuss the abundance ratio of \( r \)-process elements in EMP stars before type Ia supernovae (SNe Ia) are contributed. We do not implement SNe Ia in our simulation.

The NSM rate and the merger time (\( t_{\text{NSM}} \)) are highly uncertain. We therefore vary them by \( \sim 2 \text{ dex} \) in our simulations. We regard the fraction of NSMs to the total number of neutron stars, \( f_{\text{NSM}} \), as a parameter which determines the NSM rate. In this model, we assume the mass range of NS progenitor mass as \( 8 \leq M_{\odot} \leq 40 M_{\odot} \). We set the upper mass of NSM progenitor stars as \( 20 M_{\odot} \) from the lower limit of the mass of a black hole formation (Dominik et al. 2012). We set \( f_{\text{NSM}} = 0.01 \) as a fiducial value. The corresponding NSM rate in a MW size galaxy is \( 10^{-4} \text{ year}^{-1} \). This is within the value of the Galactic disk estimated from observed compact binaries (\( 10^{-6} \sim 10^{-3} \text{ year}^{-1} \); Abadie et al. 2010a).

The yields of NSMs are related to the rate of NSMs. [Eu/Fe] at [Fe/H] = 0 is expected to be \( \sim 0.5 \) without SNe Ia because solar Fe is estimated to be produced \( \sim 60\% \sim 65\% \) by SNe Ia and \( \sim 35\% \sim 40\% \) by CCSNe (e.g., Goswami & Prantzos 2000;
Prantzos 2008). We thus simply set the yield of r-process elements to be [Eu/Fe] = 0.5 at [Fe/H] = 0.

An observed r-process elemental abundance ratio such as [Eu/Fe] indicates that the production of r-process elements should have occurred before SNe Ia began to contribute ($\gtrsim$1 Gyr) to galactic chemical evolution (Maoz & Mannucci 2012). The minimum merger time of NSMs needs to be shorter than the typical delay time of SNe Ia. As already mentioned, the most plausible merger time of NSMs is regarded as $\sim$100 Myr (e.g., Lorimer 2008; Dominik et al. 2012). We thus set the merger time of NSMs to be 100 Myr as a fiducial value.

2.3. Definition of the Abundance of Newly Formed Stars

The abundance of a star must be identical to that of the gas which formed the star. The abundance of a newly formed star particle inherits (1) that of the SF gas particle (e.g., Raiteri et al. 1999; Shen et al. 2015; van de Voort et al. 2015) or (2) that of the average of the gas particles within an SPH kernel (e.g., Steinmetz & Müller 1994; Kobayashi & Nakasato 2011; Shen et al. 2015). Method (1) does not have a metal mixing process except for hydrodynamical mixing processes such as stellar winds, outflows, and inflows due to the SN explosion. [Eu/Fe] produced by method (1) will be discussed in Section 4.1. On the other hand, method (2) models a simple metal mixing process. We use a metallicity averaged over 32 neighboring gas particles in an SPH kernel to a newly born star particle. The region can be regarded as that of the SF region, which corresponds to $\sim$10$^4 M_\odot$. This mass corresponds to the typical size of GMCs (e.g., Larson 1981; Liszt et al. 1981; Sanders et al. 1985; Solomon et al. 1987; Harris & Pudritz 1994; Heyer et al. 2009). We discuss the results of method (2) in Section 4.2.

Massive stars tend to be born in clusters and associations (Lada & Lada 2003). Clusters and OB associations form from GMCs. Observations of stars in open clusters suggest that their metallicity is homogeneous (De Silva et al. 2007a, 2007b, 2011, 2013; Bubar & King 2010; Pancino et al. 2010; Reddy et al. 2012, 2013; Ting et al. 2012). Feng & Krumholz (2014) theoretically showed that turbulent mixing in SF regions causes this homogeneity. The timescale of metal mixing is determined by the local dynamical time of SF regions ($\lesssim$1 Myr). This timescale is much shorter than the typical timescale of star formation ($\gtrsim$10 Myr) in the slow star formation model (Zuckerman & Evans 1974; Krumholz & Tan 2007). We thus assume that the metals are instantaneously mixed in SF regions. We discuss the effect of different implementation of abundance ratios in galaxies in Sections 4.1 and 4.2.

2.4. Models of dSphs

We follow the initial conditions of dSph models adopted in Revaz et al. (2009) and Revaz & Jablonka (2012). We assume the density profile of dark matter, $\rho$, as follows:

$$\rho = \frac{\rho_c}{1 + (r/r_c)^2},$$

where $\rho_c$ is the central density and $r_c$ is the core radius. Gas particles are also distributed along with the profile. We set $r_c = 1.0$ kpc, $r_{\text{max}} = 7.1$ kpc, and $M_{\text{tot}} = 7 \times 10^8 M_\odot$ according to Revaz & Jablonka (2012). We adopt a mass ratio of gas to dark matter particles of 0.15 (baryon fraction, $f_b \equiv \Omega_b/\Omega_m$).

The value of $f_b$ is taken from Planck Collaboration XVI (2014).

Following Revaz et al. (2009), we assume an isotropic velocity dispersion of dark matter particles, $\sigma(r)$, for a spherical distribution (Hernquist 1993; Binney & Tremaine 2008),

$$\sigma^2(r) = \frac{1}{\rho(r)} \int_r^{\infty} dr' \rho(r') \frac{\partial \Phi(r')}{\partial r'},$$

where $\Phi(r)$ is the gravitational potential. For gas particles, we set the velocity equal to zero and an initial temperature of $10^4$ K. For both dark matter and gas particles, we adopt a gravitational softening length ($\epsilon_g$) of 28 pc for runs with an initial total number ($N$) of $2^{14}$, $\epsilon_g = 14$ pc for runs with $N = 2^{16}$, $2^{17}$, and $2^{18}$, and $\epsilon_g = 7$ pc for runs with $N = 2^{19}$. We run our simulations over 14 Gyr. The parameters of our model galaxies are listed in Table 2. Table 3 summarizes all of the runs discussed in this paper.

3. CHEMO-DYNAMICAL EVOLUTION OF DSPhS

3.1. Dynamical Evolution of dSph Models

We discuss the chemodynamical evolution of model s000 to confirm that the parameter set of this model is appropriate for the case of dSphs. Parameter dependence is discussed in the Appendix.

Figure 1 shows the evolution of the spatial distribution of gas and stars in model s000. The upper panels of Figure 1 show the gas density maps of model s000 at 0, 1, 5, and 10 Gyr from the beginning of the simulation. The gas monotonically collapses during the first 1 Gyr. Then, the gas density is reduced by star formation and the gas outflow by energy feedback of SNe. The red colored area in the upper panels of Figure 1 corresponds to the star-forming region where the number density of gas is larger than 100 cm$^{-3}$. As shown in this figure, the SF region is strongly confined at the center of the galaxy. The red area is largest at 1 Gyr. This indicates that star formation is most active after $\sim$1 Gyr from the beginning of the simulation.

The lower panels of Figure 1 show stellar density maps at 0, 1, 5, and 10 Gyr. The distribution of stars at 1 Gyr is associated with the high-density region of gas (red region in Figure 1). As shown in these figures, stars continuously form in the inner region of this model galaxy for over 10 Gyr and the stellar density distribution expands with time from the center to the outer region. At 10 Gyr, the morphology of the galaxy becomes spherically symmetric.

In order to quantitatively discuss the structural and dynamical properties of the models, we investigate their radial profiles. Figure 2 shows the radial profiles of model s000. We define the galactic center using the potential minimum. The values in each point are calculated in each bin from the center to the outer region.

Figure 2(a) shows the time variation of the dark matter density profile. At 1 Gyr, the dark matter follows the initial density profile given in Equation (5). After the collapse in the first 1 Gyr, the shape of the dark matter profile does not change over 10 Gyr.

Figure 2(b) shows the time variation of the gas density profile. The inner region ($\lesssim$1 kpc) of the gas density profile follows the evolution of the dark matter density profile. The outer region of the gas is blown away due to the outflow induced by SNe. In addition, the total amount of gas is reduced
because of star formation. However, gas still remains even at 10 Gyr. As in the Appendix, all of our models have gas at 10 Gyr. The observed LG dSphs, in contrast, have no or little gas (e.g., McConnachie 2012). This result suggests that physical processes such as ram pressure and tidal stripping are required to remove all gas from dSphs (Mayer et al. 2006; Nichols et al. 2014).

As shown in Figure 2(c), the stellar density profile of our simulation well reproduces observations. In Figure 2(c), we present the stellar density profiles. Stars are distributed within ~1 kpc, which is consistent with the observed tidal radii (~0.5–3 kpc) of dSphs in the LG (Irwin & Hatzidimitriou 1995). The density profile of stars is basically associated with the dark matter density profile.

Figure 2(d) shows the stellar velocity dispersion profile. The observed stellar velocity dispersion of dSphs is almost constant within ~1 kpc from the center (Walker et al. 2009). Model s000 has properties similar to the observed radial stellar velocity dispersion profiles inside 1 kpc from the center in the LG dSphs.

3.2. Time Variations of the SFR

Figure 3 shows the time variation of the SFR in model s000 (red curve) and the observed values of the Fornax and Sculptor dSphs (de Boer et al. 2012a, 2012b). The SFR of model s000 peaks at ~2 Gyr. Gas density increases with accretion (see Figure 2(b)) and finally reaches the threshold density for star formation. On the other hand, SN feedback drives gas away from the inner region to the outer region (Hopkins et al. 2011). Because of the shallow gravitational potential and high threshold density for star formation (n_{th} = 100 cm^{-3}), SN feedback significantly affects the timescale of gas accretion. It therefore takes a long time (~1 Gyr) to reach the SFR peak. The SFR of model s000 (~10^{-3} M_{\odot} yr^{-1}) is consistent with the observed value of the Fornax and Sculptor dSphs inferred from color–magnitude diagram analysis; ~10^{-3} M_{\odot} yr^{-1} (de Boer et al. 2012a, 2012b). The SFR of model mExt (magenta curve) will be discussed in Section 4.3.

3.3. Metallicity Distribution

Metallicity distribution is one of the best properties to test the reliability of chemical evolution models. Figure 4 shows comparisons of the metallicity distribution of model s000 with observations. The observed values are taken from the Fornax (Kirby et al. 2010) and the Sculptor dSphs (Kirby et al. 2009, 2010; Kirby & Cohen 2012). The metallicity distribution of model s000 is almost consistent with the observed value of the Sculptor dSph. The metallicity at the peak of the distribution of model s000 is [Fe/H] = −1.57, which is lower than that of the Fornax dSph, [Fe/H] = −1.06 (Kirby et al. 2013). This is because we do not implement SNe Ia in this model, while the Fornax dSph must be significantly affected by the metal ejection of SNe Ia (e.g., Kirby et al. 2010). If we take into account the products of SNe Ia, the metallicity at the peak of the metallicity distribution is expected to be shifted by ~0.5 dex to the higher metallicity, which is closer to the value of the Fornax dSph.

4. ENRICHMENT OF r-PROCESS ELEMENTS IN dSphs

4.1. Enrichment of r-process Elements without Metal Mixing in a Star-forming Region

In this section, we discuss [Eu/Fe] as a function of [Fe/H] predicted by model s000. In model s000, the metallicity of a star inherits that of the gas particle from which the star was formed, according to method (1) in Section 2.3. Figure 5 shows [Eu/Fe] as a function of [Fe/H] predicted by model s000. We also use the observed data of the Galactic halo and several dSphs, i.e., the Carina, Draco, Leo I, Sculptor, and Ursa Minor dSphs (SAGA database; Suda et al. 2008, 2011, 2014; Yamada et al. 2013), excluding carbon-enhanced stars, which may be affected by gas transfer in binaries. We also exclude stars in the Fornax dSph because some of them have extremely high [Eu/Fe] (>0.5 dex) due to significant contamination of the r-process (Letarte et al. 2010). As shown in Figure 5, highly r-process enhanced stars, [Eu/Fe] >1 (so-called r-II stars), are over-abundant. In addition, r-deficient stars in −2 < [Fe/H] < −1 are predicted. Such low [Eu/Fe] stars are not seen in the observations. These stars are not simply caused by the delayed production of Eu by NSMs. In fact, the average value of [Eu/Fe] does not increase with metallicity at around [Fe/H] ~ −2. The significant dispersions of chemical components among the gas particles seem to be rather essential. The relations between the galactic age and the abundances of Fe and Eu imply the cause for such large dispersions.

Figure 6(a) shows [Fe/H] as a function of time. Metallicity obviously increases with time as CCSNe produce iron. The metallicity, however, has more scatter at earlier times, especially during the first few Gyr. After that, stars formed later are enriched by more numerous CCSNe, and as a result the dispersion of stellar metallicity decreases with time. We denote those stars which are formed from the gas enriched only by a single CCSN by black circles in Figure 6(a). Their metallicity is widely distributed over ~3 dex. These stars are concentrated only in ≤2 Gyr.

Figure 6(b) shows [Eu/H] as a function of time. In contrast to Figure 6(a), large star-to-star scatter of [Eu/H] remain throughout the whole evolution of the galaxy. As shown in black circles in Figure 6(b), gas particles affected by one NSM remain over 10 Gyr. One of the causes of this must be in the low rate of NSMs. The rate of NSMs is 100 times lower than that of CCSNe in this model. The total number of NSMs may not be enough to converge the [Eu/H] in this model.

In addition to the low NSM rate, the efficiency of gas mixing in this model seems to cause unnatural large scatters in [Eu/H]. If a star particle contains products from a single NSM, the value of [Eu/H] must be determined by the distance from the NSM which enriched the SF gas particle. However, as shown in Figure 6(b), these stars are distributed with almost the same dispersion for more than 5–10 Gyr, which is much longer than the merger time.
of NSMs. This implies that gas particles never change the abundance of Eu, unless other NSMs enrich them again, though gas clouds are actually expected to interact with others.

In fact, observations of open clusters show that stellar metallicity is quite homogeneous in each cluster (e.g., De Silva et al. 2007a, 2007b, 2011, 2013; Bubar & King 2010; Pancino et al. 2010; Reddy et al. 2012, 2013; Ting et al. 2012). The gas in the SF region may be homogenized by hydro-dynamical effects such as turbulent mixing (Feng & Krumholz 2014).

In addition, previous studies have suggested that the standard SPH simulations without metal mixing tend to predict a lower

| Model   | $N$  | $m_{DM}$ ($10^3 M_\odot$) | $m_{gas}$ ($10^3 M_\odot$) | $r_g$ (pc) | $n_{th}$ ($10^3$ cm$^{-3}$) | $T_{th}$ (10$^3$ K) | $\epsilon_{SN}$ ($10^{51}$ erg) | $N_{ngb}$ | Mixing   | $t_{NSM}$ (Myr) | $f_{NSM}$  |
|---------|------|---------------------------|-----------------------------|------------|--------------------------|------------------|-----------------------------|----------|----------|----------------|-----------|
| s000    | $2^{19}$ | 2.3                       | 0.4                         | 7          | 100                      | 1                | 1                           | 32       | no       | 100                   | 0.01      |
| m000    | $2^{19}$ | 2.3                       | 0.4                         | 7          | 100                      | 1                | 1                           | 32       | yes      | 100                   | 0.01      |
| mN16    | $2^{19}$ | 2.3                       | 0.4                         | 7          | 100                      | 1                | 1                           | 16       | yes      | 100                   | 0.01      |
| mN64    | $2^{19}$ | 2.3                       | 0.4                         | 7          | 100                      | 1                | 1                           | 64       | yes      | 100                   | 0.01      |
| m014    | $2^{14}$ | 72.6                      | 12.8                        | 28         | 100                      | 1                | 1                           | 32       | yes      | 100                   | 0.01      |
| m016    | $2^{16}$ | 18.2                      | 3.2                         | 14         | 100                      | 1                | 1                           | 32       | yes      | 100                   | 0.01      |
| m017    | $2^{17}$ | 9.1                       | 1.6                         | 14         | 100                      | 1                | 1                           | 32       | yes      | 100                   | 0.01      |
| m018    | $2^{18}$ | 4.5                       | 0.8                         | 14         | 100                      | 1                | 1                           | 32       | yes      | 100                   | 0.01      |
| mExt    | $2^{19}$ | 2.3                       | 0.4                         | 7          | 0.1                      | 30               | 0.03                        | 32       | yes      | 100                   | 0.01      |
| m10     | $2^{19}$ | 2.3                       | 0.4                         | 7          | 100                      | 1                | 1                           | 32       | yes      | 100                   | 0.01      |
| m500    | $2^{19}$ | 2.3                       | 0.4                         | 7          | 100                      | 1                | 1                           | 32       | yes      | 500                   | 0.01      |
| m0.001  | $2^{19}$ | 2.3                       | 0.4                         | 7          | 100                      | 1                | 1                           | 32       | yes      | 100                   | 0.001     |
| m0.1    | $2^{19}$ | 2.3                       | 0.4                         | 7          | 100                      | 1                | 1                           | 32       | yes      | 100                   | 0.01      |

Note. Parameters adopted in our models: (1) Model: name of our models. Models named “000” adopt the fiducial parameter set. Model s000 is discussed in Sections 3 and 4.1. Models m000 to m018 are discussed in Section 4.2. Model mExt is discussed in Section 4.3. Models m10 and m500 are discussed in Section 4.4. Models m0.001 and m0.1 are discussed in Section 4.5. (2) $N$: initial total number of particles. (3) $m_{DM}$: mass of one dark matter particle. (4) $m_{gas}$: initial mass of one gas particle. (5) $r_g$: gravitational softening length. (6) $n_{th}$: threshold density for star formation. (7) $T_{th}$: threshold temperature for star formation. (8) $\epsilon_{SN}$: SN feedback energy. (9) $N_{ngb}$: number of nearest neighbor particles. (10) Mixing: with (yes) or without (no) metal mixing in star-forming region. (11) $t_{NSM}$: merger time of NSMs. (12) $f_{NSM}$: fraction of NSMs.
amount of gas with low metallicity and a higher metallicity for inter-galactic medium (Wiersma et al. 2009; Shen et al. 2010). Shen et al. (2015) suggest that it is difficult to reproduce the observed [Eu/Fe] as a function of [Fe/H] without metal mixing in the SF region.

On the other hand, the fiducial model of van de Voort et al. (2015) reproduces the observed [Eu/Fe] of metal-poor stars, although they adopt the same definition of metallicity as in our model s000. They suggest that large-scale metal mixing, such as that in galactic winds and hydrodynamical flows, is important to reproduce the observed [Eu/Fe] as a function of [Fe/H]. In their model, NSMs eject metals in the region of $3.5 \times 10^6 M_\odot$, which is much larger than the swept-up mass of NSMs ($\sim 10^4 M_\odot$). The treatment of van de Voort et al. (2015) is identical to the implementation of metal mixing.
4.2. Effects of Metal Mixing on Enrichment of r-Process Elements

As discussed in the previous section, the effect of the mixing of enriched gas must be essential to account for the observed values of $[\text{Eu}/\text{Fe}]$ in metal-poor stars. Therefore, we take into account the effect of metal mixing according to method (2) in Section 2.3, and we adopt the average metallicity of gas particles in the SPH kernel of the progenitor gas particle for the metallicity of newly formed stars. Figure 7 shows $[\text{Eu}/\text{Fe}]$ as a function of $[\text{Fe}/\text{H}]$ with the metal mixing model, m000. Model m000 has the same parameter set for s000, except for the effect of metal mixing in the SF region (see Table 3). As shown in this figure, the r-deficient stars with $[\text{Fe}/\text{H}]$ of $-2$ to $-1$ seen in Figure 5 disappear due to metal mixing. The fraction of r-II stars is also reduced in this model due to the adoption of averaged metallicity in the SF region. Model m000 apparently reproduces the observational tendency of $[\text{Eu}/\text{Fe}]$ in metal-poor stars much better than the model s000. This result therefore suggests that metal mixing in the SF region is a fairly important physical process for reproducing the observed $[\text{Eu}/\text{Fe}]$ as a function of $[\text{Fe}/\text{H}]$.

The predicted distribution of $[\text{Eu}/\text{Fe}]$ must be affected by the mass of the mixed gas $M_{\text{mix}}$ and the initial total number of particles ($N$). We define $M_{\text{mix}} = N_{\text{tot}}m_{\text{gas}}$. The mass of one gas particle $m_{\text{gas}}$ is proportional to $N^{-1}$. Table 4 lists the examined values of the parameters and the corresponding mixing mass.
(\(M_{\text{mix}}\)). Figure 9(a) shows the median value and the dispersion of \([\text{Eu}/\text{Fe}]\) for models which have different \(N_{\text{ngb}}\). The dispersion of \([\text{Eu}/\text{Fe}]\) becomes smaller with larger \(N_{\text{ngb}}\) as shown in this figure. When we increase \(N_{\text{ngb}}\), the value of \(M_{\text{mix}}\) increases and a larger mass fraction of gas in the galaxy is mixed. Due to the effects of increasing \(M_{\text{mix}}\), the dispersion becomes smaller in the models with a larger value of \(N_{\text{ngb}}\).

Figure 9(b) shows the median value of \([\text{Eu}/\text{Fe}]\) as a function of the \([\text{Fe/H}]\) of models which have different \(N\). As shown in Figure 9(b), the dispersion of \([\text{Eu}/\text{Fe}]\) shows a similar tendency irrespective of \(N\), i.e., it decreases with increasing metallicity. When we adopt the larger value of \(N\), more star particles are produced i.e., the number of metal mixing events increases. This means that metals are more mixed in the SF region if \(M_{\text{mix}}\) is constant. However, \(M_{\text{mix}}\) is defined as proportional to \(N^{-1}\). Models with a larger value of \(N\) have a smaller value of \(M_{\text{mix}}\). The effects of increasing \(N\) are canceled by decreasing \(M_{\text{mix}}\). Thus, the dispersion is not affected by \(N\).

### 4.3. The Relationship Between the Relative \(r\)-process Abundance Ratio and the SFR

The value and scatters in the abundance ratio of \([\text{Eu}/\text{Fe}]\) must be affected by SFR, especially for metal-poor stars. In order to examine the effect of SFR, we consider \([\text{Eu}/\text{Fe}]\) as a function of \([\text{Fe/H}]\) with the model mExt, in which extremely weak SN feedback energy (\(\epsilon_{\text{SN}} = 3 \times 10^{49}\) erg) and a low threshold density for star formation (\(n_{\text{th}} = 0.1\) cm\(^{-3}\)) are assumed (Table 3). According to Appendix A.2, the weaker feedback model produces a higher SFR and the model with a smaller value of \(n_{\text{th}}\) shifts the peak of SFR to the earlier time. Since mExt has lower values of \(\epsilon_{\text{SN}}\) and \(n_{\text{th}}\), stars are more easily produced compared to model m000. The SFR of model mExt during the first 1 Gyr rises rapidly and is larger than \(10^{-2} M_{\odot} \text{yr}^{-1}\). The peak SFR reaches \(\sim 10^{-1} M_{\odot} \text{yr}^{-1}\), while that of m000 is \(\lesssim 10^{-3} M_{\odot} \text{yr}^{-1}\). The SFR of model mExt at \(\lesssim 1\) Gyr is much higher than the observational values (Figure 3).

Figure 10 shows \([\text{Eu}/\text{Fe}]\) as a function of \([\text{Fe/H}]\) in model mExt. This model predicts significantly different \([\text{Eu}/\text{Fe}]\) compared with m000 (Figure 7), although both models adopt the same initial distribution of gas particles. Model mExt produces a distribution of \(r\)-deficient stars around \([\text{Fe/H}] \sim -2\). In addition, no stars are produced below \([\text{Fe/H}] \sim -3\). This difference is related to the timescale of chemical evolution in the early phase of galaxy formation. For model m000, the median metallicity of gas particles at 1 Gyr is \([\text{Fe/H}] = -3.32\). On the other hand, the median metallicity of gas particles in mExt is \([\text{Fe/H}] = -0.91\) at 1 Gyr. The SFE of model mExt is estimated to be \(\sim 0.1–1\) Gyr\(^{-1}\). The value of SFE is comparable to some other inhomogeneous chemical evolution studies (Argast et al. 2004; Cescutti et al. 2015; Wehmeyer et al. 2015). In model mExt, chemical evolution proceeds much faster than in m000 due to the high SFR of mExt (\(\sim 10^{-2} M_{\odot} \text{yr}^{-1}\)). The \([\text{Eu}/\text{Fe}]\) as a function of \([\text{Fe/H}]\) in model mExt is inconsistent with the observation due to fast chemical evolution by the high SFR. This result suggests that the SFR and SFE in the early phase of dSphs are
\[ t = dSph \]

is consistent with the observed value of the Fornax dSph (de Boer et al. 2012b). This SFR is also consistent with the sub-halo models of Ishimaru et al. (2015; Case 1 in their model suggests that the appropriate value of the SFE for a sub-halo with a stellar mass of \( 10^7 \) is the order of SFR as \( \sim 10^{-3} M_\odot \text{yr}^{-1} \)).

4.4. Merger Times of NSMs

In this section, we discuss the effect of merger time of NSMs. Figure 11 shows the obtained [Eu/Fe] as a function of [Fe/H] by NSMs with different merger times \( (t_{\text{NSM}}) \). Eu in Figures 11(a) and (b) is produced by NSMs with \( t_{\text{NSM}} = 10 \text{ Myr} \) (mt10) and 500 Myr (mt500), respectively. Although mt10 has a slightly smaller fraction of stars in \(-3 < [\text{Fe/H}] < -2\) than model m000, the global relative abundance ratio is similar to m000 \( (t_{\text{NSM}} = 100 \text{ Myr}) \). Contrary to models m000 and mt10, the model with a much longer merger time, such as 500 Myr in mt500, shows large scatters in [Eu/Fe] at higher metallicity and cannot account for the observed scatters in \[ [\text{Fe/H}] \sim -3. \]

Figure 12 shows [Fe/H] as a function of the substantial galactic age, i.e., the elapsed time from the rise of major star formation. As shown in Figure 3, we can regard the major star formation as arising from 600 Myr from the beginning of the calculation. The average metallicity of stars is almost constant during the first \( \sim 300 \text{ Myr} \). Due to the low SFE of the galaxy, the spatial distribution of metallicity is highly inhomogeneous in \( \sim 300 \text{ Myr} \). In this epoch, since most gas particles are enriched only by a single SN, the metallicity of stars is mainly determined simply by the distance from each SN to the gas particles which formed the stars. Therefore, NSMs with \( t_{\text{NSM}} \sim 100 \text{ Myr} \) can account for the observation of EMP stars as well as those with \( t_{\text{NSM}} \sim 10 \text{ Myr} \). In contrast, metallicity is well correlated with the galactic age after \( \sim 300 \text{ Myr} \), irrespective of the distance from each SN to the gas particles. Because SN products have already been well mixed in a galaxy, the stellar metallicity is determined by the number of SNe which enriched the stellar ingredients. Therefore, if the merger time of the NSMs is much longer than \( \sim 300 \text{ Myr} \), it is too long to reproduce observations.

4.5. The Rate of NSMs

The yields of r-process elements in our models are related to the NSM rate as already mentioned in Section 2.2, although the Galactic rate of NSMs is highly uncertain. The estimated Galactic NSM rate is \( 10^{-6} \text{ to } 10^{-3} \text{ year}^{-1} \) based on three observed binary pulsars (Abadie et al. 2010a). Table 5 lists the yields of models discussed here. Figure 13 shows the predicted [Eu/Fe] as a function of [Fe/H] assuming different NSM rates. Figures 13(a) and (b) represent models with the NSM fractions \( f_{\text{NSM}} = 0.001 \) (mt0.001) and \( f_{\text{NSM}} = 0.1 \) (mt0.1), respectively. The corresponding NSM rate in a MW-like galaxy is...
Figure 12. [Fe/H] as a function of time of model m000. The horizontal axis is plotted from 600 Myr from the start of the simulation. Black curve is the average of the metallicity in each age. Contour is the same as in Figure 5.

Note. The columns correspond to the name of models, fraction of NSMs \( f_{\text{NSM}} \), and total yields of \( r \)-process elements \( Y_{r} \). Fraction of NSMs is the fraction of stars that cause NSMs in the mass range 8–20 \( M_{\odot} \).

| Model | \( f_{\text{NSM}} \) | \( Y_{r} \) (\( M_{\odot} \)) |
|-------|----------------|------------------|
| Mr0.001 | 0.001 | 10\(^{-5}\) |
| Mr0.01 | 0.01 | 10\(^{-2}\) |
| Mr0.1 | 0.1 | 10\(^{-3}\) |

\(~10^{-5} \text{year}^{-1}\) (Mr0.001) and \(~10^{-3} \text{year}^{-1}\) (Mr0.1). Model Mr0.001 predicts larger scatter and a smaller number of stars at \([\text{Fe/H}] < -3\) than in m000. Model Mr0.001 has [Eu/Fe] dispersion more than 3 dex at \([\text{Fe/H}] = -2\). In addition, there remains ~1 dex dispersion even for stars with \([\text{Fe/H}] > -2\). In contrast, model Mr0.1 predicts smaller scatter than m000, although it does not seem to be inconsistent with observations. Such tendencies are also seen in Argast et al. (2004), Komiya et al. (2014), and van de Voort et al. (2015).

Our fiducial model, m000 reproduces the observed \( r \)-process ratio as discussed in Section 4.2. The NSM rate of m000 for a MW-like galaxy is \(~10^{-4} \text{year}^{-1}\). The total mass of \( r \)-process elements produced by each NSM corresponds to \(~10^{-2} M_{\odot}\). This value is consistent with recent nucleosynthesis calculations: \(10^{-3} M_{\odot}\) to \(10^{-2} M_{\odot}\) (e.g., Gorily et al. 2011; Korobkin et al. 2012; Bauswein et al. 2013; Hotokezaka et al. 2013; Wanajo et al. 2014).

Argast et al. (2004) construct an inhomogeneous chemical evolution model of the MW halo. Their model has difficulty reproducing [Eu/Fe] by NSMs with a Galactic NSM rate of \(2 \times 10^{-4} \text{year}^{-1}\) due to high SFE. The [Eu/Fe] produced by their model is similar to that of mExt (Figure 10).

From the discussion above, an NSM rate of \(~10^{-3} \text{year}^{-1}\) in a MW size galaxy is preferable to reproduce the observed [Eu/Fe]. This rate is consistent with the estimated galactic NSM rate from the observed binary pulsars (Abadie et al. 2010a). Planned gravitational detectors, such as KAGRA, advanced LIGO, and advanced VIRGO (Abadie et al. 2010b; Kuroda & LCGT Collaboration 2010; Accadia et al. 2011; LIGO Scientific Collaboration 2013) are expected to detect gravitational waves from 10–100 NSM events per year.

Figure 13. [Eu/Fe] as a function of time with different rate of NSMs. (a) Mr0.001 (\( f_{\text{NSM}} = 0.001 \)). (b) Mr0.1 (\( f_{\text{NSM}} = 0.1 \)). Symbols are the same as in Figure 5.

5. SUMMARY

We have carried out numerical simulations of the chemodynamical evolution of dSphs using the \( N \)-body/SPH code ASURA to investigate the enrichment history of \( r \)-process elements. This study suggests that NSMs with a merger time of \(~100 \text{Myr}\) and a Galactic NSM rate of \(~10^{-4} \text{year}^{-1}\) can explain the dispersion of \( r \)-process abundances [Eu/Fe] in reasonable agreement with observations in EMP stars. This study supports that NSMs are the major astrophysical site of the \( r \)-process. Our isolated dSph models reproduce the basic properties of the observed LG dSphs such as radial profiles, time variations of the SFR, and metallicity distribution. Here, we summarize the main results.
(1) The abundance ratio of [Eu/Fe] produced in our models without metal mixing in SF regions has too large of a dispersion. This is because metals in a gas particle do not diffuse to other particles throughout the evolution of galaxies.

(2) Models with metal mixing in the SF region reproduce the observed [Eu/Fe] distribution and its scatter as a function of [Fe/H]. Our model shows good convergence of the resolution. We show that NSMs with \( t_{\text{NSM}} = 100 \) Myr are favorable for reproducing the observed [Eu/Fe] as a function of metallicity. This result implies that the metal mixing process is critical to reproduce the [Eu/Fe] distribution. In addition, this study suggests that the SFR of dSphs in the early epoch of their evolution (\( \sim 1 \) Gyr) is \( \lesssim 10^{-3} M_{\odot} \) yr\(^{-1}\).

(3) NSMs with merger times of \( \lesssim 300 \) Myr account for the observed abundance of EMP stars. This is because metallicity is not correlated with time in \( \sim 300 \) Myr from the start of the simulation due to the low SFE of the model galaxy.

(4) This study suggests that the Galactic NSM rate to account for the observed r-process abundance scatters is \( \sim 10^{-4} \) year\(^{-1}\). The total mass of r-process elements ejected by one NSM is \( \sim 10^{-2} M_{\odot}\), which is consistent with the value suggested by nucleosynthesis studies (\( 10^{-3} \) to \( 10^{-2} M_{\odot}\)). The next generation gravitational detectors KAGRA, advanced LIGO, and advanced VIRGO are expected to detect gravitational waves from NSMs and their event rate would be over 10 per year. Their detections will give us a reliable galactic NSM rate.

In this study, we have focused on the enrichment history of r-process elements in isolated dSphs with fixed mass. To fully understand the enrichment history of r-process elements in the LG galaxies, it is important to show how the mass and size of galaxies affect the enrichment of r-process elements.

Recent observations also suggest the low abundance of r-process elements ([Ba/Fe]\( \sim -1 \)) in stars with [Fe/H] \( \sim -3.5 \). These stars provide clues to understand the astrophysical site(s) of r-process elements and the metal enrichment in the first galaxies. Some studies suggest that the r-process abundance of these stars can be explained by the short merger time channel (\( \sim 1 \) Myr) of NSMs (Ishimaru et al. 2015) or the accretion of materials from the inter-stellar medium onto the Population III stars (Komiya et al. 2014). Since we have only focused on the star-to-star scatter of [Eu/Fe] in stars with [Fe/H] \( \sim -3 \) in this paper, we have not discussed the origin of these stars. It is profitable to discuss the origin of these stars by the detailed simulation of galaxies.

To address all of these issues, we must understand how the MW halo formed. We need to clarify the relation between the building block galaxies of the MW and the present LG dSphs. Efforts are now underway to extend our numerical simulations of the chemodynamical evolution of dSphs to larger scale simulations of the MW in order to fully understand the enrichment of r-process elements in the MW and confirm the validity of the scenario of hierarchical structure formation.

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APPENDIX

PARAMETER DEPENDENCE

A.1. Radial Profile

We compare models with different threshold densities for star formation \( n_{\text{th}} \), dimensionless SFE parameters \( c_r \), and SN feedback energies \( \epsilon_{\text{SN}} \). Table 6 lists all of the models discussed here. Figure 14 shows the radial profiles of our models. The horizontal axis of Figure 14 is the distance from the galactic center. Figure 14(a) shows the dark matter density

Table 6

| Model | \( n_{\text{th}} \) cm\(^{-3}\) | \( c_r \) | \( \epsilon_{\text{SN}} \) \( 10^3 \) erg |
|-------|----------------|--------|------------------|
| s000  | 100            | 0.033  | 1                |
| sn010 | 10             | 0.033  | 1                |
| sc50  | 100            | 0.5    | 1                |
| se01  | 100            | 0.033  | 0.1              |

Note. Parameters adopted in our models: (1) Model: name of our models. (2) \( c_r \): dimensionless star formation efficiency parameter. (3) \( n_{\text{th}} \): threshold density for star formation. (4) \( \epsilon_{\text{SN}} \): SN feedback energy.

Figure 14. Radial profiles of models of different parameters at \( t = 5.0 \) Gyr. Red triangles, green diamonds, blue pentagons, and magenta hexagons represent model s000, sn10 (\( n_{\text{th}} = 10 \) cm\(^{-3}\)), sc50 (\( c_r = 0.5 \)), and se01 (\( \epsilon_{\text{SN}} = 10^{39} \) erg), respectively. (a) Radial dark matter density profile. (b) Radial gas density profile. (c) Radial stellar density profile. (d) Radial velocity dispersion profile.

\( ^{10} \) Barium (Ba) can also be regarded as r-process elements in [Fe/H] \( \lesssim -3 \).
profile. We find that all of the models have similar dark matter profiles. The dark matter profile is not affected by physical parameters such as threshold density for star formation, dimensionless SFE parameters, and SN feedback energy.

Gas density, stellar density, and stellar velocity dispersion profiles have variations among these models. The gas density of sn10 and se01 is lower than that of s000 (Figure 14(b)). In these models, most of the gas is consumed in the early phase of their evolution. The gas density of se01 is truncated at 0.3 kpc while the gas profiles of the other models continue over 10 kpc. This is because the feedback energy in se01 is too weak to blow the gas away to the outer region of the galaxy.

Stellar density profiles for all of the models (Figure 14(c)) are truncated within a few kiloparsecs, which is consistent with the observed truncation radius (∼0.5–3 kpc) of dSphs in the LG (Irwin & Hatzidimitriou 1995). In sn10, stars distribute to a larger radius than in the other models. When a low value of \( n_{th} \) is used, stars can form in the outer region of the galaxy. If the SN feedback is weak (model se01), stellar distribution concentrates on the central region of the galaxy.

Figure 14(d) shows the velocity dispersion profile. All models except for se01 are consistent with the observed radial velocity dispersion profiles inside 1 kpc from the center in the LG dSphs (Walker et al. 2007, 2009). Model se01 has a higher velocity dispersion at the center of our model galaxy due to the high central concentration of stars.

In contrast to \( n_{th} \) and \( \epsilon_{SN} \), the dimensionless SFE parameter \( c_s \) does not greatly affect the radial profiles. Figure 14 shows that all of the profiles of s000 (red curve) and sc50 (blue curve) are similar, although they have different values of the dimensionless SFE parameter. These features suggest that the radial properties of galaxies are insensitive to the value of \( c_s \) when we adopt a reasonable value of \( n_{th} \) (=100 cm\(^{-3}\); Saitoh et al. 2008).

A.2. Time Variations of the SFR and Metallicity Distribution

Figures 15 and 16 show SFR as a function of time and metallicity distribution, respectively. SFR as a function of time and metallicity distribution are characterized by the threshold density for star formation and SN feedback energy. Model sn10 has lower \( n_{th} \) (=10 cm\(^{-3}\)) than that of s000 (\( n_{th} = 100 \) cm\(^{-3}\)). The second peak of SFR of sn10 is earlier than s000. This reflects that the time required to reach \( n_{th} \) is shorter than s000 because of the low \( n_{th} \) value in sn10. In addition, the first peak of SFR of sn10 is higher than s000. Gas is consumed by star formation and removed by outflow at <0.1 Gyr in sn10. Its SFR is therefore ∼2 dex lower than s000. The early bursty star formation of sn10 produces more metal-poor stars than s000 (see green dashed and red curves in Figure 16). Higher SFR of sn10 ∼0.1 Gyr produces more CCSNe in this phase. CCSNe produce outflows. Model sn10 thus loses a larger amount of gas around ∼0.1 Gyr. Chemical evolution of sn10, therefore, quenches at >0.1 Gyr and produces only a few metal-rich stars.

SN feedback energy also significantly affects the time variation of the SFR and metallicity distribution. The SN feedback energy of se01 (\( \epsilon_{SN} = 10^{50} \) erg) is 10 times smaller than that of s000 (\( \epsilon_{SN} = 10^{53} \) erg). The peak of the SFR of se01 is over 1 dex higher than that of s000. SN feedback energy gives thermal energy to gas particles. This prevents the collapse of gas particles. As a result, star formation is suppressed due to SN feedback energy. The SN feedback energy of se01 is too weak to suppress star formation. The peak of the SFR of se01 is thus ∼1 dex higher than s000. Gas is consumed for star formation due to high SFR around 2 Gyr of se01, and the SFR at >4 Gyr is eventually suppressed. Due to the low SN feedback energy in model se01, the peak metallicity distribution of se01 is ∼0.5 dex higher metallicity than in s000.
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On the other hand, the value of the dimensionless SFE parameter does not significantly affect the results. Models s000 and sc50 have different values of $c_v = 0.033$ and 0.5, respectively. The time variation of the SFR and metallicity distribution of sc50 is, however, similar to that of s000. This result suggests that the time variation of the SFR and metallicity distribution are insensitive to the value of $c_v$ if we use a reasonable value of $n_{th} (=100 \text{ cm}^{-3})$. The slightly lower metallicity of sc50 than s000 is due to the slightly lower SFR of sc50 than s000. This result suggests that the value of $c_v$ does not affect the metallicity distribution as well as radial profiles and the SFR. When we adopt $n_{th} = 100 \text{ cm}^{-3}$, it takes much longer local dynamical time to flow from the reservoir ($n_{th} \approx 1 \text{ cm}^{-3}$) to the SF regions ($n_{th} \gtrsim 100 \text{ cm}^{-3}$). This timescale does not depend on $c_v$ (Saitoh et al. 2008). Our results are thus independent of $c_v$.

These results suggest that the time variation of the SFR and metallicity distribution is significantly affected by the threshold density for star formation and SN feedback energy. The low $n_{th}$ model (sn10) produces too many EMP stars. In contrast, the low $c_v$ model (se01) has too many metal-rich stars. These differences in metallicity distribution are due to the difference of the time variation of the SFR among models. On the other hand, model s000 reproduces the observation of the metallicity distribution as well as the dynamical properties. Parameters of s000 are taken from the observed values. Threshold density of $n_{th} (=100 \text{ cm}^{-3})$ is taken from mean density of GMCs. SN feedback energy of $s000$ ($c_v = 10^4 \text{ erg}$) is taken from the canonical explosion energy of CCSNe (e.g., Nomoto et al. 2006). We thus treat s000 as a model that has fiducial parameter sets.

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