

Feedback effects of aspherical supernovae explosions on galaxies

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ABSTRACT

We investigate how explosions of aspherical supernovae (A-SNe) can influence star formation histories and chemical evolution of dwarf galaxies by using a new chemodynamical model. We mainly present the numerical results of two comparative models so that the A-SN feedback effects on galaxies can be more clearly seen. SNe originating from stars with masses larger than $30M_{\odot}$ are A-SNe in the “ASN” model whereas all SNe are spherical ones (S-SNe) in the “SSN” model. Each S-SN and A-SN are assumed to release feedback energy of 10^{51} erg and 10^{52} erg, respectively, and chemical yields and feedback energy of A-SN ejecta depend on angles between the axis of symmetry and the ejection directions. We find that star formation can become at least by a factor of ~ 3 lower in the ASN model in comparison with the SSN one owing to the more energetic feedback of A-SNe. As a result of this, chemical evolution can proceed very slowly in the ASN model. A-SN feedback effects can play a significant role in the formation of giant gaseous holes and energetic gaseous outflow and unique chemical abundances (e.g., high [Mg/Ca]). Based on these results, we provide a number of implications of the A-SN feedback effects on galaxy formation and evolution.

Key words: galaxies:abundances – galaxies:dwarf – galaxies:evolution – stars:formation – stars:supernovae

1 INTRODUCTION

Feedback effects of supernova (SN) explosions have long been considered to be one of key determinants in galaxy formation and evolution (e.g., Larson 1974; Dekel & Silk 1986). SN feedback effects depending on galactic properties (e.g., masses and potential depth) have been discussed extensively in variously different contexts of galaxy formation, such as the origin of the color-magnitude diagrams in elliptical galaxies (e.g., Arimoto & Yoshii 1980), the formation of galactic disks (e.g., Navarro & White 1993), global mass loss in low-mass galaxies (e.g., Dekel & Silk 1986), and the formation of cored dark matter halos in dwarfs (e.g., Governato et al. 2010). Chemodynamical simulations have played significant roles in better understanding the SN feedback effects on chemical and dynamical evolution of galaxies (e.g., Theis et al. 1992; Kawata & Gibson 2003; Revaz & Jablonka 2012).

A growing number of observational studies on host

galaxies for gamma-ray bursts (GRBs) have revealed that most of the GRB hosts at relatively low redshifts ($z < 2$) are star-forming, metal-poor, and dwarf-like galaxies (e.g., Savaglio 2008; Savaglio et al. 2009). More energetic explosion events of jet-induced supernovae are considered to be associated with the origin of long-duration GRBs (e.g., Woosley & Bloom 2003) and such supernovae are extreme cases of aspherical supernovae (“A-SNe”). Therefore, the detection of a GRB event in a galaxy implies that the galaxy has recently experienced a much larger number of A-SN events. Given that A-SNe can release a significantly more amount of energy ($\sim 10^{52}$ erg; Shigeyama et al. 2010; S10) in comparison with spherical SNe (S-SNe), it is highly likely that dwarf galaxies, like some of GRB hosts, are strongly influenced by A-SN explosions. However, even the latest chemodynamical studies (e.g., Rahimi & Kawata 2012) have not investigated chemical and dynamical influences of A-SN explosions on galaxies.

The purpose of this Letter is to show, for the first time, that A-SN explosions can significantly influence gas dynamics, star formation histories, and chemical evolution of dwarf

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Table 1. Description of the basic parameter values and some results for representative models.

Model name	$M_{\text{dm,dw}}$ ^a	$M_{\text{s,dw}}$ ^b	$M_{\text{g,dw}}$ ^c	SN-type for $8 \leq m_{\text{sn}}/M_{\odot} \leq 30$ ^d	SN-type for $30 < m_{\text{sn}}/M_{\odot}$	ϵ_{sf} ^e
ASN	20.0	1.0	1.0	S-SN	A-SN	9.5×10^{-3}
SSN	20.0	1.0	1.0	S-SN	S-SN	1.1×10^{-1}

^a The initial total mass of dark matter halo in a dwarf in units of $10^8 M_{\odot}$.

^b The initial total mass of stellar disk in a dwarf in units of $10^8 M_{\odot}$.

^c The initial total mass of gaseous disk in a dwarf in units of $10^8 M_{\odot}$.

^d The mass of each SN is denoted as m_{sn} and A-SN and S-SN represent aspherical and spherical SNe, respectively.

^e The star formation efficiency defined as $M_{\text{ns,dw}}/M_{\text{g,dw}}$, where $M_{\text{ns,dw}}$ is the total mass of new star formed until $T = 1.4$ Gyr.

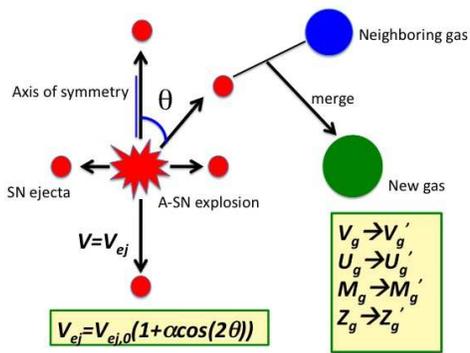


Figure 1. An illustrative explanation for the adopted new method to implement feedback effects of A-SNe on galaxies. After the explosion of A-SN, its gaseous ejecta can soon merge/mix with the neighboring gas (particle) so that velocity (V_g), internal energy (U_g), mass (M_g), and metallicity (Z_g) of the gas can change. The ejection velocity (V_{ej}) and chemical abundances of the ejecta depend on the angle (θ) between the axis of symmetry and the neighboring gas (particle). The A3 model of S10 (with $\alpha = 7/9$) is adopted for calculating V_{ej} and chemical yields.

galaxies by using our new chemodynamical simulations of dwarf galaxy evolution. In order to more clearly show the importance of A-SN feedback effects in dwarf galaxy evolution, we present the results of the following comparative models. One is the “ASN” model in which SNe with their original masses larger than $30M_{\odot}$ can become A-SNe whereas other low-mass ($\leq 30M_{\odot}$) can become S-SNe. The other is the “SSN” model in which all SNe are S-SNe. Although recent observations have shown that some massive stars are fast-rotating (e.g., Groh et al. 2009), it is observationally unclear what fraction of massive stars with masses larger than $30M_{\odot}$ can become A-SNe. In the present paper, we consider two extreme cases and thereby try to clearly point out the importance of A-SNe in galaxy evolution.

2 THE MODEL

We investigate chemical evolution and star formation history of an isolated dwarf disk galaxy by using our original chemodynamical code (“GRAPE-SPH”) that can be run on a GPU cluster and the latest version of GRAPE (GRAVity PipE, GRAPE-DR) which is the special-purpose computer for gravitational dynamics (Sugimoto et al. 1990). We have

revised our original GRAPE-SPH code (Bekki 2009) by incorporating chemical yields both from S-SNe (Tsujiimoto et al. 1995) and from A-SNe (S10) so that we can investigate not only dynamical and hydrodynamical influences of A-SN feedback on dwarf galaxies but also chemical enrichment processes by A-SNe in a self-consistent way. More details of the revised code (including code performance) will be given in our forthcoming paper (Bekki 2012, in preparation) and the results of one-zone chemical evolution models with ASN for dwarf galaxies will be discussed in Bekki et al. (2012, B12).

2.1 Dwarf disk galaxy

A dwarf is modeled as a fully self-gravitating system and assumed to consist of a dark matter halo, a stellar disk, and a gaseous one. The density profile of the dark matter halo with the total mass of $M_{\text{dm,dw}}$ is represented by that proposed by Salucci & Burkert (2000):

$$\rho_{\text{dm}}(r) = \frac{\rho_{\text{dm},0}}{(r + a_{\text{dm}})(r^2 + a_{\text{dm}}^2)}, \quad (1)$$

where $\rho_{\text{dm},0}$ and a_{dm} are the central dark matter density and the core (scale) radius, respectively. Recent observational and numerical studies have shown that the adopted “cored dark matter” halos are reasonable for describing dark matter distributions in low-mass galaxies (e.g., Governato et al. 2010). We adopt $M_{\text{dm,dw}} = 2.0 \times 10^9 M_{\odot}$ and $a_{\text{dm}} = 2.1$ kpc (i.e., $2.5 \times 10^8 M_{\odot}$ within a_{dm}).

The stellar component of the dwarf is modeled as a bulge-less stellar disk with the total mass of $M_{\text{s,dw}}$ and the size of 1.8 kpc. The radial (R) and vertical (Z) density profiles of the stellar disk are assumed to be proportional to $\exp(-R/R_0)$ with scale length $R_0 = 0.36$ kpc and to $\text{sech}^2(Z/Z_0)$ with scale length $Z_0 = 0.072$ kpc, respectively. We adopt $M_{\text{s,dw}} = 10^8 M_{\odot}$ in this study. In addition to the rotational velocity caused by the gravitational field of disk and dark halo components, the initial radial and azimuthal velocity dispersions are assigned to the disc component according to the epicyclic theory with Toomre’s parameter $Q = 1.5$. The vertical velocity dispersion at a given radius is set to be 0.5 times as large as the radial velocity dispersion at that point. Dwarf irregular galaxies are observed to have gas disk extending to approximately twice the Holmberg radius (R_{H}) and some of them have gas out to $(4-7)R_{\text{H}}$ (e.g., Hunter 1997). We consider this observation and adopt an exponential gas disk with the size of 7.2 kpc and the scale length of 1.44 kpc. The total gas mass ($M_{\text{g,dw}}$) is set to be $10^8 M_{\odot}$.

The radiative cooling processes dependent on gaseous metallicities are properly included by using the MAPPING III code (Sutherland & Dopita 1993). A gas particle is converted into a new star if (i) the local dynamical time scale is shorter than the sound crossing time scale (mimicking the Jeans instability) and (ii) the local velocity field is identified as being consistent with gravitationally collapsing (i.e., $\text{div } \mathbf{v} < 0$). We do not include additional model parameters for star formation, such as the threshold gas density, mainly because we try to more clearly demonstrate the differences in dwarf galaxy evolution between ASN and SSN models in this study. The star formation efficiency is chosen such that the efficiency can be proportional to $\rho_g^{1.5}$ (to mimic the Schmidt law), where ρ_g is the local gas density. The initial temperature is set to be 1.7×10^2 K. The gas disk is assumed to have (i) a radial metallicity gradient with the central metallicity of $[\text{Fe}/\text{H}] = -1.32$ and a negative radial gradient of -0.2 dex kpc^{-1} and (ii) a SN-II like enhanced $[\alpha/\text{Fe}]$ ratio (e.g., $[\text{Mg}/\text{Fe}] \approx 0.4$). Non-instantaneous recycling of gaseous ejecta from type Ia and II SNs and low-mass AGB stars are properly considered for chemical enrichment processes associated with star formation. The effects of UV background radiation, which could thermally heat up gas and thus suppress star formation in dwarfs, are not included.

2.2 A new feedback scheme

As shown in S10, chemical yields and velocities (V_{ej}) of SN ejecta in A-SNe depend strongly on angles (θ) between the axis of symmetry and ejection directions. The axis of symmetry is set to be parallel to the z -axis of the adopted coordinate system in which the x - y plane coincides with the disk of a dwarf. B12 have recently shown that such θ -dependences of chemical yields in A-SNe are important for understanding chemical evolution of dwarf galaxies. We here adopt the Model A3 of S10 in which the total explosion energy (E_{asn}) is assumed to be 10^{52} erg. Owing to the θ -dependences of chemical yields and V_{ej} , we adopt different models for feedback effects of S-SNe and A-SNe and the model for A-SNe is described as follows (See Figure 1 for an illustrative explanation of the A-SN feedback model).

A new stellar particle can release feedback energy of A-SNe to their neighboring gas particles 1.2×10^6 yr after its formation. The half of the energy is used for the increase of the internal energy of the gas (“thermal feedback”) and the other half is used to change the momentum of the gas (“kinematic feedback”). As a result of this, each of the neighboring gas particles changes its mass (M_g), internal energy (U_g), velocity (V_g), and metallicity (Z_g). Guided by the results of 2D hydrodynamical simulations for axisymmetric supernova explosions by S10, we assume that the ejection velocity of A-SN is described as follows:

$$V_{\text{ej}}(\theta) \propto 1 + (7/9) \cos(2\theta). \quad (2)$$

Therefore V_{ej} is larger for SN ejecta close to jet (i.e., axis of symmetry).

We first estimate θ for each j -th neighboring gas particle around i -the new stellar one and then change $M_{g,j}$, $U_{g,j}$, $V_{g,j}$, and $Z_{g,j}$ according to θ -dependent chemical yields and feedback energy. The new velocity of the j -th gas particle after A-SN feedback effects ($V'_{g,j}$) is determined by the following equation (i.e., conservation of linear momentum):

$$(M_{g,j} + m_{\text{ej}}(\theta))V'_{g,j} = M_{g,j}V_{g,j} + m_{\text{ej}}(\theta)V_{\text{ej}}(\theta), \quad (3)$$

where $m_{\text{ej}}(\theta)$ is the mass of the A-SN ejecta at θ . Likewise, the new thermal energy ($U'_{g,j}$) is determined by the following equation:

$$(M_{g,j} + m_{\text{ej}}(\theta))U'_{g,j} = M_{g,j}U_{g,j} + m_{\text{ej}}(\theta)U_{\text{ej}}(\theta), \quad (4)$$

where $U_{\text{ej}}(\theta)$ is the specific internal energy of the A-SN ejecta at θ and proportional to $V_{\text{ej}}^2(\theta)$. Therefore $E_{\text{asn}} = \int m_{\text{ej}}(\theta)(0.5V_{\text{ej}}^2(\theta) + U_{\text{ej}}(\theta))d\theta$. The increase of chemical abundances in the k -th heavy element due to chemical enrichment by A-SN of the i -th new stellar particle is described as follows:

$$\Delta Z_{g,j,k} = m_{\text{ej}}(\theta)A_{\text{ej},k}(\theta), \quad (5)$$

where $A_{\text{ej},k}(\theta)$ is the chemical yield of A-SN (normalized by mass). Each neighboring particle around a SN can receive the same amount of metals. Metal-diffusion between SPH particles is not included, which could possibly overestimate the local abundance inhomogeneity.

We adopt the same models of S-SN feedback effects as those used in previous formation models of disk and elliptical galaxies (e.g., Navarro & White 1993; Kawata & Gibson 2003). The total energy of S-SN (E_{ssn}) is set to be 10^{51} erg and the half is used for thermal feedback and the other half is used for kinematic feedback. We adopt the canonical Salpeter initial mass function (IMF) with the slope of -2.35 and the lower and upper mass cut-offs being $0.1M_{\odot}$ and $50M_{\odot}$, respectively. Therefore, the number ratio of SNe with masses of $[8 - 50]M_{\odot}$ and those with masses larger than $30M_{\odot}$ is ~ 10 . However, A-SNe can significantly influence evolution of dwarf galaxies owing to $E_{\text{asn}} = 10E_{\text{ssn}}$.

2.3 Simulation setup

The total number of particles used for each component (dark matter, stellar disk, and gaseous one) in a simulation is 200,000 (i.e., 600,000 in total). The gravitational softening length is fixed at 175pc for dark matter and 21pc for stellar and gaseous disks. We investigate the star formation history and chemical evolution (in particular Mg, Ca, and Fe) of dwarf galaxies for 1.4 Gyr. Table 1 briefly summarizes the parameter values used in the two comparative ASN and SSN models. In the following, T in a simulation represents the time that has elapsed since the simulation started.

3 RESULTS

Figure 2 shows the time evolution of the mass distribution of the inner gas disk projected onto the x - y plane in the ASN model. As new stars form from high-density regions of the inner gas disk, explosions of S-SNe and A-SNe can strongly disturb the surrounding local regions through thermal and kinematic feedback effects ($T = 0.56$ Gyr). As a result of this, the local regions with very low gas densities, which can be identified as giant “HI” holes, can be formed in the inner disk. These HI holes are connected with filamentary gaseous structures with relatively high densities, where star formation can still continue. A stellar bar can form by $T = 0.84$ Gyr and a weak bar-like structure of gas can be seen in the central region of the disk. However, strong feedback effects

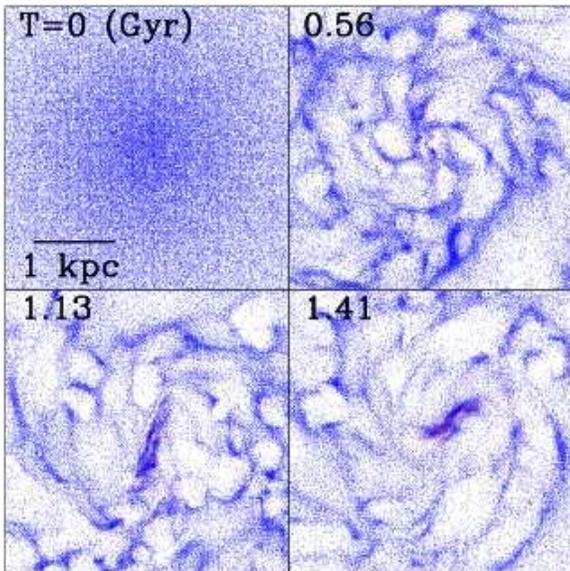


Figure 2. The time evolution of the distribution of gas (blue) and new stars (red) in the inner disk projected onto the x - y plane for the A-SN model. The bar in the lower left corner of each panel measures 1 kpc and the time T is shown in the upper left corner.

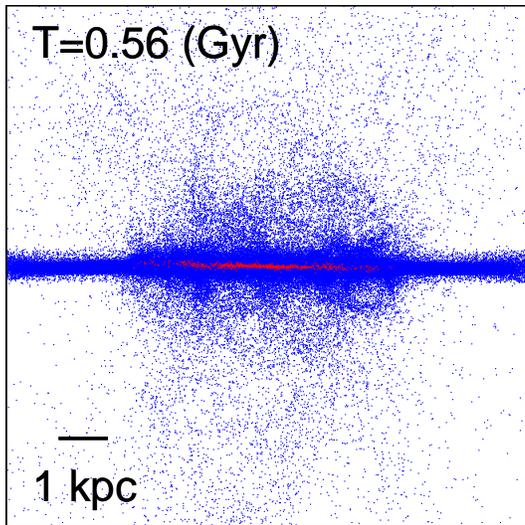


Figure 3. The distribution of gas (blue) and new stars (red) projected onto the x - z plane at $T = 0.56$ Gyr for the ASN model.

of A-SN can prevent the formation of massive, high-density gaseous regions in the center and thus severely suppress the secondary starburst there ($T = 1.13$ and 1.41 Gyr). The total mass of gas converted into new stars ($M_{\text{ns,dw}}$) is only $9.7 \times 10^5 M_{\odot}$ for the ~ 1.4 Gyr evolution, which means that the stellar surface density can increase only by $\sim 1\%$.

Figure 3 shows clearly that a significant fraction of the inner gas disk can be expelled from the dwarf owing to the strong SN feedback effects. The total mass of gas with $|z| > 10Z_0$ ($=0.64$ kpc), which can be regarded as gas being expelled from the disk as “stellar wind”, is $1.8 \times 10^7 M_{\odot}$. The rate of this stellar wind is $3.2 \times 10^{-10} M_{\odot} \text{ yr}^{-1}$, which is significantly larger than that in the SSN model. About

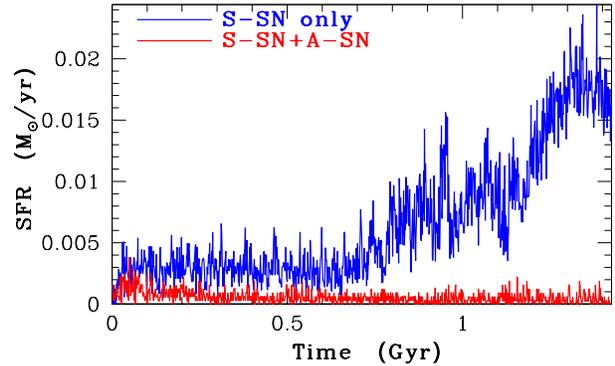


Figure 4. The time evolution of star formation rate for the SSN (blue) and ASN (red) models.

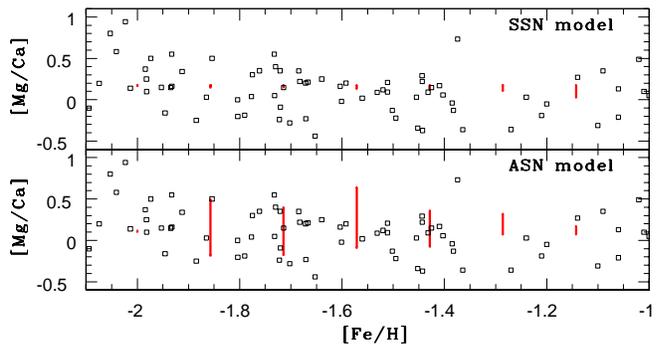


Figure 5. The simulated ranges of $[\text{Mg}/\text{Ca}]$ (thick vertical red lines) for the SSN (upper) and ASN (lower) models. The small open squares are observational data for dwarfs in the Local Group from B12 which compiled the observational data from different dwarf spheroidals (e.g., Koch 2009).

$1.2 \times 10^7 M_{\odot}$ of the gas can be finally located outside the virial radius (15.6 kpc) of the dwarf at $T = 1.4$ Gyr so that the gas can not return back to the original gas disk for further star formation. The dwarf can finally have a metal-poor gaseous halo with the total mass of $1.3 \times 10^7 M_{\odot}$.

Figure 4 shows that global star formation in the ASN model is more strongly suppressed in comparison with the SSN one owing to the stronger SN feedback effects in the ASN model. The mean star formation rate for $0 \text{ Gyr} \leq T \leq 0.56$ Gyr (before stellar bar formation) is only $9.1 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$, which is by a factor of ~ 3 smaller than that in the SSN model. The star formation rate can not rise even after the bar formation and ends up with the mean rate of $6.8 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$ for the 1.4 Gyr evolution. The difference in star formation rates between the two models becomes even more remarkable after the bar formation ($T > 0.8$ Gyr), because gas inflow due to the bar can trigger a secondary starburst in the SSN model. The star formation efficiency ($\epsilon_{\text{sf}} = M_{\text{ns,dw}}/M_{\text{g,dw}}$) is estimated to be 0.0097 in the ASN model.

Figure 5 shows one of remarkable differences in chemical abundances of new stars at $T = 1.4$ Gyr between the ASN and SSN models in which mean $[\text{Mg}/\text{Ca}]$ of the ejecta for massive SNe is ~ 0.2 . The $[\text{Mg}/\text{Ca}]$ abundance ratios in the ASN (SSN) model range from -0.18 (0.03) to 0.64

(0.18): the large [Mg/Ca] scatter at a given [Fe/H] range can be clearly seen only in the ASN model. The rather high [Mg/Ca] (> 0.2) in the ASN model is due to chemical enrichment by A-SNe (i.e., due to ejecta with high [Mg/Ca]). As shown in Figure 5, large scatter in [Mg/Ca] can be clearly seen in dwarf galaxies of the Local Group. Therefore the present results imply that one of possible explanations for the large [Mg/Ca] scatter in the dwarfs is chemical pollution of interstellar medium of the dwarfs by ASN ejecta at their formation epochs. As a result of very low star formation efficiency, chemical enrichment does not proceed efficiently so that the average [Fe/H] of new stars can be kept low (~ -1.5) in the ASN model.

4 DISCUSSION AND CONCLUSIONS

We have first demonstrated that A-SNe can more strongly influence star formation histories of dwarf galaxies than S-SNe owing to their larger amount of feedback energy. It should be however stressed that the number fraction of A-SNe among all SNe with masses larger than $30M_{\odot}$ (f_{asn}) is assumed to be 1 in the present A-SN model. This means that the present numerical study could overestimate the feedback effects of A-SNe, because it is observationally unclear what a reasonable value is for f_{asn} in dwarf galaxies. Nagataki et al. (1997) showed that the observed light curve of 1987A in the LMC is consistent with the predictions of their aspherical SN explosion models. Recent observations on the presence of fast-rotating massive stars (Groh et al. 2009), which are progenitors of A-SNe, imply that A-SNe could be ubiquitous. These results imply that A-SNe could be major populations among SNe and thus that future numerical simulations of galaxy formation and evolution would need to include A-SNe self-consistently.

Bekki & Tsujimoto (2012) failed to explain the observed low [Ca/Fe] (~ -0.2) and high [Mg/Ca] (~ 0.3) at [Fe/H] > -0.5 for the stars of the LMC in their chemical evolution models with S-SNe only and therefore suggested that A-SNe might play a role in chemical enrichment processes of the LMC. B12 have recently shown that the observed high [Mg/Ca] of the LMC and dwarfs can be reproduced well by the chemical evolution models with A-SNe. As demonstrated in the present chemodynamical simulations, higher [Mg/Ca] can be achieved only in the A-SN model. These previous and present studies thus suggest that the observed [Mg/Ca] can be an indicator of the long-term influences of A-SNe on chemical evolution of galaxies.

The present study predicts that if dwarf disk galaxies continue to experience A-SN feedback effects, they can end up with galaxies with faint luminosities and low surface brightness (LSB) owing to very low conversion efficiency of gas into new stars. This prediction implies that (i) the origin of LSB galaxies could be closely associated with significantly stronger influences of A-SN feedback effects (i.e., higher f_{asn}) and (ii) LSB might well have unique chemical abundance patterns (e.g., high [Mg/Ca]). The present results also suggest that f_{asn} is a key parameter that can control how the SN feedback can strongly suppress star formation and thereby determine the structures (e.g., surface mass densities) of dwarf galaxies. For example, if f_{asn} is significantly higher (> 0.1) in a dwarf at its formation epoch,

then the dwarf could finally become a very faint LSB galaxy like ultra-faint dwarfs.

Investigation of A-SN feedback effects on galaxies have just started in the present study and the better and realistic ways to implement feedback effects from different SNe (e.g., how to include kinematic effects etc) need to be carefully investigated. It is our future work to investigate how galaxy formation processes through hierarchical merging of subgalactic clumps can change if more energetic A-SN feedback effects are properly included in our future chemodynamical simulations.

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