THE HISTORY OF THE COSMIC SUPERNOVA RATE DERIVED FROM THE EVOLUTION OF THE HOST GALAXIES

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ABSTRACT

We make a prediction of the cosmic supernova rate history as a composite of the supernova rates in spiral and elliptical galaxies. We include the metallicity effect on the evolution of Type Ia supernova (SN Ia) progenitors, and construct detailed models for the evolutions of spiral and elliptical galaxies in cluster and field to meet the latest observational constraints. In the cluster environment, the synthesized cosmic star formation rate (SFR) has an excess at $z \gtrsim 3$ corresponding to the SFR in ellipticals and a shallower slope from the present to the peak at the redshift of $z \sim 1.4$ compared with Madau’s plot. In the field environment, we assume that ellipticals form at such a wide range of redshifts as $1 \lesssim z \lesssim 4$. The synthesized cosmic SFR has a broad peak around $z \sim 3$, which is in good agreement with the observed one. The resultant cosmic SFRs lead to the following predictions for the cosmic SN Ia rate: 1) The SN Ia rate in spirals has a break at $z \sim 2$ due to the low-metallicity inhibition of SNe Ia, regardless of cluster or field. 2) At high redshifts, the SN Ia rate has a strong peak around $z \sim 3$ in the cluster, whereas in the field much lower is expected, reflecting the difference in the formation epochs of ellipticals.

Subject headings: cosmology: theory — galaxies: abundances — galaxies: evolution — supernovae: general

1. INTRODUCTION

The search for high-redshift supernovae has been extensively conducted mainly to determine cosmological parameters by the Supernova Cosmology Project (Perlmutter et al. 1999) and the High-z Supernova Search Team (Riess et al. 1998). High-redshift supernovae can also provide useful information on the star formation history in the universe. Type Ia supernovae (SNe Ia) have been discovered up to $z \sim 1.32$ (Gilliland, Nugent & Phillips 1999), and the SN Ia rate has been estimated up to $z \sim 0.5$ (Pain et al. 1996; Pain 1999). With the Next Generation Space Telescope, both SNe Ia and Type II supernovae (SNe II) will be observed up to $z \sim 4$. The SN Ia rate is directly connected with the star formation rate (SFR), and the SN Ia rate also can trace the SFR with a SN Ia progenitor model. In a theoretical approach, the cosmic SN Ia rate as a function of redshift has been constructed using the observed cosmic SFR (Ruiz-Lapuente & Canal 1998; Yungelson & Livio 1998; Sadat et al. 1998; Madau, Della Valle & Panagia 1998; Kobayashi et al. 1998).

The cosmic SFR has been estimated observationally up to $z \sim 5$ from UV and Hα luminosity densities with the help of spectral population synthesis models (e.g., Madau et al. 1996; Connolly et al. 1997). The observed cosmic SFR by Madau et al. (1996) shows a peak at $z \sim 1.4$ and a sharp decrease to the present. However, UV luminosities which are converted to the SFRs may be affected by the dust extinction (Pettini et al. 1998). Recent updates of the cosmic SFR show some different features (Tresse & Maddox 1998; Gronwall 1998; Treyer et al. 1998; Hughes et al. 1998; Glazebrook et al. 1999; Steidel et al. 1999), one of which suggests that a peak lies around $z \sim 3$.

Among the several attempts to calculate the cosmic SN Ia rate using the observed cosmic SFR, Kobayashi et al. (1998) predicts that the cosmic SN Ia rate drops at $z \sim 1 - 2$, due to the metallicity-dependent SN Ia rate. In their SN Ia progenitor model, the accreting white dwarf (WD) blows a strong wind to reach the Chandrasekhar (Ch) mass limit (Hachisu, Kato & Nomoto 1996, 1999). If the iron abundance of the progenitors is as low as [Fe/H] $\lesssim -1$, then the wind is too weak for SNe Ia to occur. This model successfully reproduces the observed chemical evolution of the solar neighborhood such as the evolution of the oxygen to iron ratio and the abundance distribution function of disk stars (Kobayashi et al. 1998).

Their finding that the occurrence of SNe Ia depends on the metallicity of the progenitor systems implies that the SN Ia rate strongly depends on the history of the star formation and metal-enrichment therein. The universe is composed of different morphological types of galaxies and therefore the cosmic SFR is a sum of the SFRs for different types of galaxies. As each morphological type has a unique star formation history, we should decompose the cosmic SFR into the SFR belonging to each type of galaxy and calculate the SN Ia rate for each type of galaxy.

In this paper, first we construct the detailed evolution models for different types of galaxies which are compatible with the stringent observational constraints, and apply them to reproduce the cosmic SFR for two different environments, i.e., the cluster and the field. Secondly we confirm that the metallicity-dependent SN Ia progenitor model which has been already tested for the solar neighborhood can explain the present supernova rates for all types of galaxies. Finally combining the above SN Ia model with the self-consistent galaxy models, we calcu-
late the SN Ia rate history for each type of galaxy and predict the cosmic SN Ia rate as a function of redshift.

In the next section, we will describe our computational method of the galaxy evolution with our SN Ia progenitor model. In section 3, we construct the star formation histories of spirals and ellipticals, and predict their supernova rate histories in section 4. In section 5, we make a prediction of the cosmic supernova rates as a composite of different types of galaxies in cluster and field. Conclusions are given in section 6.

2. MODELS

2.1. Type Ia Supernova Model

The progenitors of the majority of SNe Ia are most likely the Ch mass WDs (e.g., Nomoto, Iwamoto & Kishimoto 1997a for a recent review), although the sub-Ch mass models might correspond to some peculiar subluminous SNe Ia. The early time spectra of the majority of SNe Ia are in excellent agreement with the synthetic spectra of the Ch mass models, while the spectra of the sub-Ch mass models are too blue to be compatible with observations (Höflich & Khokhlov 1996; Nugent et al. 1997). For the evolution of accreting WDs toward the Ch mass, two scenarios have been proposed: One is a double-degenerate (DD) scenario, i.e., merging of double C+O WDs with a combined mass surpassing the Ch mass limit (Iben & Tutukov 1984; Webbink 1984), and the other is a single-degenerate (SD) scenario, i.e., accretion of hydrogen-rich matter via mass transfer from a binary companion (e.g., Nomoto et al. 1994 for a review). The issue of DD versus SD is still debated for a review). The issue of DD versus SD is still debated (e.g., Saio & Nomoto 1985, 1998; Segretain, Chabrier & Mochkovitch 1997), and the lifetime of SNe Ia predicted by the DD scenario is too short to be consistent with the chemical evolution of the solar neighborhood (Kobayashi et al. 1998).

Our SD scenario has two progenitor systems: One is a red-giant (RG) companion with the initial mass of \( M_{\text{RG,0}} \sim 1M_\odot \) and an orbital period of tens to hundreds days (Hachisu et al. 1996, 1999ab). The other is a near main-sequence (MS) companion with an initial mass of \( M_{\text{MS,0}} \sim 2 - 3M_\odot \) and a period of several tenths of a day to several days (Li & van den Heuvel 1997; Hachisu et al. 1999a). In our SD scenario, a C+O white dwarf accretes H-rich materials from the companion star and grows its mass to the Ch mass to explode as an SN Ia. Optically thick winds from the mass accreting WD play an essential role in stabilizing the mass transfer and escaping from forming a common envelope. The optically thick winds are driven by a strong peak of OPAL opacity at \( \log T(K) \sim 5.2 \) (e.g., Iglesias & Rogers 1993). Since the peak is due to iron lines, the optically thick winds depend strongly on the iron abundance (Kobayashi et al. 1998; Hachisu & Kato 1999).

The metallicity effect on SNe Ia is clearly demonstrated by the size of regions to produce SNe Ia in the diagram of the initial orbital period versus the initial mass of the companion star in Figure 2 of Kobayashi et al. (1998). The SN Ia regions are much smaller for smaller metallicity. The initial mass ranges of the companion stars with the metallicity of \( Z = 0.004 \) for a white dwarf with the mass of \( 1M_\odot \) are \( 0.9M_\odot \lesssim M_{\text{RG,0}} \lesssim 1.5M_\odot \) for the WD+RG system and \( 1.8M_\odot \lesssim M_{\text{MS,0}} \lesssim 2.6M_\odot \) for the WD+MS system, which are adopted in our chemical evolution model.

To produce SNe Ia, the wind velocity at the photosphere should exceed the escape velocity. The metallicity dependence of the optically thick winds is shown in Figure 1 of Kobayashi et al. (1998), which predicts the low-metallicity inhibition of SNe Ia. Since there are only few WDs with the mass of \( M_{\text{WD,0}} \sim 1.1M_\odot \) (Umeda et al. 1999) and only the initial WD mass of \( M_{\text{WD,0}} \lesssim 1.2M_\odot \) can produce an SN Ia (Nomoto & Kondo 1991), SN Ia events occur only for the progenitors with \( [\text{Fe/H}] \gtrsim -1.1 \).

In our chemical evolution model, the progenitors of SNe Ia are assumed to have main sequence masses in the range of \( m_{\text{MS},0} = 3M_\odot \) and \( m_{\text{MS},u} = 8M_\odot \), and form C+O white dwarfs. The distribution function of the companion stars (mass donors) is assumed to be \( \phi_0(m) \propto m^{-\alpha} \) with the slope of \( \alpha = 0.35 \). This slope is determined from the distribution function of the initial mass of the companions which is taken from the observed mass ratio distribution in binaries (Dugan & Mayor 1991). The fraction of primary stars which eventually produce SNe Ia is defined as \( b \) in equation (10) in section 2.2. The parameter \( b \) is determined from the \( \chi^2 \) test to reproduce the chemical evolution of the solar neighborhood. We get \( 0.04 \lesssim b_{\text{MS}} \lesssim 0.055 \) for WD+MS binaries and 0.01 \( \lesssim b_{\text{RG}} \lesssim 0.04 \) for WD+RG binaries under 2\( M_{\text{MS}} + 0.05 \text{M}_{\odot} \sim 0.12 \), and we adopt \( b_{\text{MS}} = 0.05 \) and \( b_{\text{RG}} = 0.02 \) as the best fit. Figure 1 shows the value of \( b \) as a function of the companion mass \( m_{\alpha} \) (upper panel) and the lifetime of companions i.e., lifetime of SNe Ia \( t_{\text{Ia}} \) (lower panel). In the lower panel, the solid and dashed lines are for \( Z = 0.002 \) and \( Z = 0.02 \), respectively. The left component in the upper panel and the right in the lower panel are for WD+RG binaries, and the other components are for WD+MS binaries.

2.2. Galactic Evolution Model

Allowing the material infall from outside, we construct a simplified model of the galactic chemical evolution (Tinsley 1980). Let \( \psi \) be the SFR and \( R_{\text{in}} \) the infall rate, then the time \( t \) variation of the gas fraction \( f_{\text{g},i} \) and the fraction of heavy element \( Z \) in the gas \( Z_{i} \) are given by the following equations:

\[
\frac{df_{\text{g},i}}{dt} = \psi + E_{\text{Ia}} + R_{\text{in}}. \tag{1}
\]

\[
\frac{d(Z_{i}f_{\text{g}})}{dt} = Z_{i} \psi + E_{\text{z},i} + E_{\text{z},i,\text{II}} + E_{\text{z},\text{Ia}} + Z_{i,\text{in}}R_{\text{in}}. \tag{2}
\]

The initial conditions are \( f_{\text{g},i} = 0 \) and \( Z_{i} = 0 \). The gas fractions \( f_{\text{g}} \) is normalized by the total mass supplied until \( t \to \infty \). The metallicity \( Z \) is defined as the sum of \( Z_{i} \) from C to Zn.

We adopt the exponential form of infall rate with a infall timescale \( \tau_{\text{I}} \) as

\[
R_{\text{in}} = \frac{1}{\tau_{\text{I}}} \exp(-t/\tau_{\text{I}}). \tag{3}
\]

The metallicity of the infall gas \( Z_{i,\text{in}} \) is assumed to be 0. The SFR is assumed to be proportional to the gas fraction (Schmidt 1959) as

\[
\psi = \frac{1}{\tau_{\text{S}}} f_{\text{g}}. \tag{4}
\]
where $\tau_m$ is the timescale of star formation.

From dying stars, gas is ejected into the interstellar medium by mass loss and SNe II at a rate of $E$ and by SNe Ia at a rate of $E_{\text{Ia}}$. Heavy elements are ejected at a rate of $E_{z_i,\text{Ia}}$, $E_{z_i,\text{II}}$, and $E_{z_i,\text{Ia}}$ by mass loss, SNe II, and SNe Ia, respectively. These ejection rates are given by the following equations:

$$E = \int_{m_i}^{m_u} (1 - w_m) \psi(t - \tau_m) \phi(m) \, dm,$$

$$E_{z_i,\text{Ia}} = \int_{m_i}^{m_u} \left(1 - w_m - p_{z_i,\text{Ia}} \right) Z_i(t - \tau_m) \psi(t - \tau_m) \phi(m) \, dm,$$

$$E_{z_i,\text{II}} = \int_{m_i}^{m_u} p_{z_i,\text{II}} \psi(t - \tau_m) \phi(m) \, dm,$$

$$E_{\text{Ia}} = m_{\text{CO}} R_{\text{Ia}},$$

$$E_{z_i,\text{Ia}} = m_{\text{CO}} p_{z_i,\text{Ia}} R_{\text{Ia}}.$$ Here $m_{\text{CO}} = 1.38 M_\odot$ is the white dwarf mass at the explosion. $R_{\text{Ia}}$ denotes the SN Ia rate, which is obtained as

$$R_{\text{Ia}} = b \int_{m_{\text{max}}[p_{z_i}, m_i]}^{m_{\text{max}}[p_{z_i}, m_i]} \frac{1}{m} \phi(m) \, dm \times \int_{m_{\text{max}}[p_{z_i}, m_i]}^{m_{\text{max}}[p_{z_i}, m_i]} \frac{1}{m} \psi(t - \tau_m) \phi_{\text{Ia}}(m) \, dm.$$ As noted in section 2.1, our SN Ia scenario has two types of progenitors (i.e., WD+MS and WD+RG binaries). We calculate the SN Ia rate for each binary with each $b$, $m_{\text{Ia}}$, and $m_{\text{d},u}$, and combine them. The SN II rate $R_{\text{II}}$ is also obtained as

$$R_{\text{II}} = \int_{m_{\text{max}}[p_{z_i}, m_i]}^{m_{\text{max}}[p_{z_i}, m_i]} \frac{1}{m} \psi(t - \tau_m) \phi(m) \, dm.$$ The lower mass limit for integrals is the turning off mass $m_t$ at $t$ which is the mass of the star with the main sequence lifetime $\tau_m = t$. $\tau_m$ is taken from Kodama & Arimoto (1997) as a function of metallicity $Z$. $w_m$ is the remnant mass fraction, which is the mass fraction of a neutron star or a white dwarf. $p_{z_i,\text{II}}$ and $p_{z_i,\text{Ia}}$ are the stellar yields which are the mass fractions of newly produced and ejected heavy element $i$, which are given from the supernovae nucleosynthesis model (Tsujimoto et al. 1995; Nomoto et al. 1997b) with $p_{z_i,\text{II}} = 0$ for $m < 10 M_\odot$. We do not include the dependence of $w_m$, $p_{z_i,\text{II}}$, and $p_{z_i,\text{Ia}}$ on the stellar metallicity.

The initial mass function (IMF) is assumed to have time-invariant mass spectrum $\phi(m) \propto m^{-2}$ normalized to unity at $m_t \leq m \leq m_u$. Theoretical arguments indicate that the IMF originates from fragmentation of a gas cloud almost independently of local physics in the gas (Low & Lynden-Bell 1976; Silk 1977). A solar-neighborhood IMF would therefore be a good approximation, and we adopt the Salpeter slope of $x = 1.35$ (Salpeter 1955) and a mass range from $m_t = 0.05 M_\odot$ to $m_u = 50 M_\odot$ (Tsujimoto et al. 1997).

The time variation of stellar fraction $f_s$ is calculated as

$$\frac{df_s}{dt} = \psi - E_{\text{Ia}},$$

and the mean stellar metallicity $Z_{i,t}$ at the time $t$ is obtained from the conservation of heavy elements;

$$Z_{i,t} f_g + Z_{i,s} f_s = \int_0^t \left( E_{z_i,\text{II}} + E_{z_i,\text{Ia}} + Z_{i,\text{in}} R_{\text{in}} \right) \, dt.$$ The photometric evolution of galaxies is calculated from the summation of the simple stellar population, which is defined as a single generation of coeval and chemically homogeneous stars of various masses, and taken from Kodama & Arimoto (1997) as a function of age $t$ and metallicity $Z$. The passbands of photometric systems and the zero points are the same as Kodama & Arimoto (1997).

For a standard model, we adopt $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_0 = 0.2$, $\Lambda_0 = 0$, and the galactic age of 15 Gyr, which corresponds to the redshift at the formation epoch of galaxies of $z \sim 4.5$.

3. STARGAS FORMATION HISTORY OF GALAXIES

3.1. Spiral Galaxies

The star formation history can be inferred from the observed present-day colors of galaxies, by using the well-known technique of stellar population synthesis (Arimoto, Yoshii & Takahara 1992). In this paper, we determine the timescales $\tau_m$ and $\tau_{\text{Ia}}$ in equations (3) and (4) to reproduce both observed colors and gas fractions for four types of spirals, i.e., S0a-Sa, Sab-Sb, Sbc-Sc, and Scd-Sd. These values are summarized in Table 1. As shown in the top panel of Figure 2, earlier types of spirals form a larger fraction of stars at an early epoch, thereby having redder and smaller gas fractions at present. The excellent agreements between models and the observations are shown in middle and bottom panels of Figure 2. The resultant present metallicities and colors are tabulated in Table 2. Observational data of the present $B - V$ colors for various types of spirals are taken from Roberts & Haynes (1994). We use the gas (i.e., HI+H$_2$) fractions which are normalized by the present blue luminosity of the galaxy to avoid the uncertainty in the fractions of the dark matter. The HI mass is taken from Roberts & Haynes (1994), and the H$_2$ mass is derived from the H$_2$/HI ratios (Casoli et al. 1998).

3.2. Elliptical Galaxies

The star formation history in elliptical galaxies is controversial between the single star burst and the continuous star formation. In the former, elliptical galaxies are formed through dissipative collapse of a protogalactic cloud with a single star burst at a very early epoch (e.g., Larson 1974; Arimoto & Yoshii 1987; Kodama & Arimoto 1997). In the latter, elliptical galaxies grow through mergers of gaseous galaxies with a continuous star formation through later epoch (e.g., Kauffmann & Charlot 1998; Baugh et al. 1998).

The dissipative collapse scenario assumes that the star formation in ellipticals has stopped by a loss of gases due to a supernova-driven galactic wind (Larson 1974; Arimoto & Yoshii 1987), so that the bulk of the stars are old and have formed at $z \gtrsim 2$. The galactic wind model can well reproduce the passive evolution of colors observed in cluster ellipticals (Stanford, Eisenhardt & Dickinson 1998; Kodama
passive color evolution observed at 0
< 1 Gyr among the cluster, group and field ellipticals (Bernardi et al. 1998).

Taking into account the possibility that there exists the environmental effect on the galaxy formation, we set two models for ellipticals in the cluster and the field, respectively.

1) For cluster ellipticals, we adopt the galactic wind model. The epoch of galactic wind tgw (i.e., the epoch of the end of star formation) is determined from the dynamical potential of the galaxy (Larson 1974), and we assume tgw = 1 Gyr on the average which corresponds to the redshift of z ∼ 3. The adopted τe and τs in equations (3) and (4) are summarized in Table 1, and the resultant present metallicities and colors are in Table 2. This star formation history is constructed to reproduce the observational constraints such as the present stellar metallicity of Z ∼ 0.52 solar averaged over the whole galaxy (Kobayashi & Arimoto 1999), the present B − V color (Roberts & Hayes 1994), and the passive color evolution observed at 0 ∼ z ∼ 1 as shown in Figure 3. The observed colors are a little bluer than the colors with no evolution, which means that cluster ellipticals have passively evolved from the present to colors with no evolution, which means that cluster ellipticals are as old as cluster ellipticals (Zepf 1997; Franceschini et al. 1998; Kodama, Bower & Bell 1999). However the relation of Mg indices and velocity dispersions implies the age difference of only ∼ 1 Gyr among the cluster, group and field ellipticals (Bernardi et al. 1998).

2) For field ellipticals, we adopt the same star formation model for 34 field ellipticals in the Hubble Deep Field, using the broadband spectra (Franceschini et al. 1998).

4. THE HISTORY OF THE COSMIC SUPERNOVAE RATE

4.1. Spiral Galaxies

The observed SN II rate RII in late-type spirals is about twice the rate in early-type spirals. On the other hand, the observed SN Ia rate RIa in both types of spirals are nearly the same. Thus the present RIa/RII ratio in early-type spirals is larger than that in late-type spirals by a factor of ∼ 2. Such a difference in the relative frequency is a result of the difference in the SFR (see section 3.1), because the dependences of RIa and RIa on the SFR are different due to the different lifetimes of supernova progenitors. Therefore the observed RIa/RII ratio gives a constraint on the SN Ia progenitor model.

Figure 5 shows the predicted evolutionary change in RIa/RII ratios for early and late types of spirals, compared with the observations. The solid, dashed, and dotted lines show the results for our SN Ia model, the single delay-time model with tIa ∼ 1.5 Gyr (Yoshii, Tsuchimoto & Nomoto 1996), and the DD model (Tutukov & Yungelson 1994), respectively. In the DD model, the lifetime of majority of SNe Ia is ∼ 0.1−0.3 Gyr, so that the evolution of RIa is similar to RI. Therefore RIa/RII is insensitive to the SFR. This results in the small differences in RIa/RII among the various type of spirals, which is not consistent with observations. For the similar reason, the single delay-time model with tIa ∼ 1.5 Gyr can not be acceptable.

In our SN Ia model, if the iron abundance of progenitors is [Fe/H] ∼ −1, the occurrence of SNe Ia is determined from the lifetime of the companions, which is tIa ∼ 0.5−1.5 Gyr for MS companions and ∼ 2−20 Gyr for RG companions (see Figure 1). If SNe Ia occurred only in the MS+WD systems with relatively short lifetimes, RIa/RII would have been insensitive to the SFR. On the contrary, if SNe Ia occurred only in the RG+WD systems with longer lifetimes, the present difference in RIa/RII between early and late type spirals would have been too large, reflecting the large difference in SFR at an early epoch. Owing to the presence of these two types of the progenitor systems in our SN Ia progenitor model, the observed difference in RIa/RII can be reproduced.

4.2. Elliptical Galaxies

Figure 6 shows the SN Ia rate history in ellipticals. As noted in section 3.2, we assume that a bulk of stars in cluster ellipticals are formed at z ∼ 3 and have ages older than 10 Gyr. Thus, in the single delay-time model (dashed line) and the DD model (dotted line), the SN Ia lifetimes are too short for enough number of SNe Ia to occur at the present epoch. In ellipticals, the chemical enrichment takes place so early (see Figure 9) that the metallicity effect on SN Ia is not effective, and therefore the SN Ia rate depends almost only on the lifetime. Our SN Ia model (solid line) includes the RG+WD systems with tIa ∼ 10 Gyr, thus well reproducing the present SNe Ia rate in ellipticals.

A burst of SNe Ia occur after ∼ 0.5 Gyr from the beginning of the star formation, because SNe Ia start to occur from the MS+WD binaries at their shortest lifetime. The second peak of the SN Ia rate appears after ∼ 2 Gyr, because of the onset of SNe Ia from RG+WD binaries. If we apply the age-redshift relation in Figure 6, these two peaks appear at z ∼ 2.5 and ∼ 1.5, respectively. From z ∼ 0.2 to z ∼ 0, the SN Ia rate gradually decreases to the present by ∼ 40%. Majority of SN Ia progenitors with
Z = 0.002 have already explode at z < 0.2 and only more metal-rich SNe Ia occur at z ∼ 0. This is because lifetime τ_m of smallest mass companions (0.9 M⊙) depends on the metallicity as τ_m ∼ 11 Gyr for Z = 0.002 and τ_m ∼ 19 Gyr for Z = 0.02 (see Figure 1).

The decrease in the SN Ia rate from z ∼ 0.2 to z ∼ 0 depends also on the star formation history in ellipticals and the galactic age. If we adopt the galactic age of 12 Gyr, such decrease in the SN Ia rate do not appear. If ellipticals have undergone the relatively continuous star formation, as suggested by the hierarchical clustering simulations, the SN Ia rate might keep constant to the present. The predicted rate for H_0 = 50 km s^{-1} Mpc^{-1} adopted in our calculation is a little higher than the observations at present. We can get better fit for H_0 = 65 km s^{-1} Mpc^{-1}, because the absolute value in our model is independent of the cosmological parameters, while the observed SN Ia rate is proportional to H^2_0.

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5. COSMIC SUPERNOVA RATE

Galaxies that are responsible for the cosmic SFR have different timescales for the heavy-element enrichment, and the occurrence of supernovae depends on the metallicity therein. Therefore we should calculate the cosmic supernova rate by summing up the supernova rates in spirals and ellipticals with the ratio of the relative mass contribution. The relative mass contribution of i-th type of galaxies is obtained from the observed relative luminosity proportion c_i = 0.215, 0.185, 0.160, 0.275, and 0.165 (Pence 1976) for ellipticals, S0a-Sa, Sab-Sb, Sbc-Sc, and Scd-Sd, respectively, and the calculated mass to light ratio in B-band (M/L)_B, for each galaxy model, as given in Table 2.

The cosmic SFR is calculated as

\[
\psi_{\text{cosmic}} [M_\odot \text{yr}^{-1} \text{Mpc}^{-3}] = \rho_c \Omega_{\infty} \frac{\Sigma_i c_i (M/L)_B i}{\Sigma_i c_i (M/L)_B},
\]

We should convert the SFR per mass to the SFR per volume by multiplying a constant. This constant is constrained from the stellar fractions per comoving density at present. The gas and stellar fractions are given by

\[
\rho_g = \rho_{g0} \frac{\Sigma_i c_i (M/L)_B i \Sigma_i c_i (M/L)_B i}{\Sigma_i c_i (M/L)_B},
\]

\[
\rho_s = \rho_{s0} \frac{\Sigma_i c_i (M/L)_B i \Sigma_i c_i (M/L)_B i}{\Sigma_i c_i (M/L)_B},
\]

\[
\rho_{g0} = \text{initial comoving density of gas defined by Pei & Fall (1995), and we adopt } \rho_{g0} = 3.5 \times 10^{-3} h^{-1} \text{ to reproduce the present stellar fraction log } \Omega_{\text{gal}} = -2.3 \text{ (Fukugita, Hogan & Peebles 1998). We get the present gas fraction of log } \rho_{g0} = -3.6.
\]

The cosmic SN II or Ia rate \( \mathcal{R}_{\text{SN}} \) per luminosity and per mass are given as

\[
\mathcal{R}_{\text{SN, cosmic}} [(10^{10} L_\odot)^{-1} \text{ Century}^{-1}] = \Sigma_i c_i \mathcal{R}_{\text{SN, i}} [(10^{10} L_\odot)^{-1} \text{ Century}^{-1}],
\]

\[
\mathcal{R}_{\text{SN, cosmic}} [\text{yr}^{-1} \text{ Mpc}^{-3}] = \rho_c \Omega_{\infty} \frac{\Sigma_i c_i (M/L)_B \mathcal{R}_{\text{SN, i}} [M_\odot^{-1} \text{ Gyr}^{-1}]}{\Sigma_i c_i (M/L)_B i}.
\]

If we adopt larger \( \Omega_{\infty} \), we get larger \( \mathcal{R}_{\text{SN}} \) and thus larger \( \psi_{\text{cosmic}} \). However, the \( \mathcal{R}_{\text{SN, cosmic}} \) per luminosity does not depend on \( \Omega_{\infty} \).

5.1. In Clusters

First, we make a prediction of the cosmic supernova rates in the cluster galaxies using the galaxy models which are in good agreements with the observational constraints as shown in Figures 2 and 3. The upper panel of Figure 7 shows the cosmic SFR (solid line) as a composite of spirals (long-dashed line) and ellipticals (short-dashed line). In our galaxy models, ellipticals undergo a star burst at \( z > 3 \) and the duration of the star formation is \( \sim 1 \) Gyr, while spirals undergo relatively continuous star formation. Thus, only the SFR in spirals is responsible for the cosmic SFR at \( z < 2 \). For reference, the observed cosmic SFR in field, so-called Madau’s plot (Gallego et al. 1995, filled triangle; Lilly et al. 1996, open circle; Madau et al. 1996, open square; Connolly et al. 1997, filled circle), is also plotted. Compared with them, the predicted cosmic SFR has a little shallower slope from the present to the peak at \( z \sim 1.4 \) (see also Totani, Yoshii & Sato 1997), and the high SFR in ellipticals appears at \( z > 3 \). Such SFR in ellipticals may be hidden by the dust extinction (Pettini et al. 1998) or ellipticals may have formed at \( z \sim 5 \) (Totani et al. 1997). The recent observations reveal the controversial situation on the cosmic SFR; the slope from \( z \sim 0 \) to \( z \sim 1 \) becomes much shallower (Tresse & Maddox 1998, open pentagon; Treyer et al. 1998, filled square; Gronwall 1998) or steeper (Rowan-Robinson et al. 1997; Glazebrook et al. 1999, filled pentagon), and the SFR becomes higher at \( z > 2 \) than Madau’s plot (Hughes et al. 1998, star; Pettini et al. 1998, filled triangle) or keeps the high rate toward \( z \sim 5 \) (Steidel et al. 1999).

The lower panel of Figure 7 shows the cosmic supernova rates (solid line) as a composite of spirals (long-dashed line) and ellipticals (short-dashed line). The upper and lower three lines show the SN II and Ia rates, respectively. Our SN Ia model is in good agreement with the observed rate at \( z \sim 0.5 \) (Pain et al. 1996, filled circle; Pain 1999, filled square). The SN Ia rate in spirals drops at \( z_{\text{IA}} \sim 2 \) because of the low-metallicity inhibition of SNe Ia. In ellipticals, the chemical enrichment takes place so early that the metallicity is large enough to produce SNe Ia at \( z > 3 \). The two peaks of SN Ia rates at \( z \sim 2.5 \) and \( z \sim 1.5 \) come from the MS+WD and RG+WD binary systems, respectively (see section 4.2). The redshifts at these two peaks depend on the assumed formation epochs of ellipticals. If SNe Ia at \( z > 2 \) are observed with their host galaxies with the Next Generation Space Telescope, we can precisely test the metallicity effect by finding the drop of the SN Ia rate in spirals. Figure 8 is the same as the lower panel of Figure 7, but for the supernova rate per volume.

The redshifts \( z_{\text{IA}} \) where SN Ia rate drops depends on the speed of the chemical enrichment in the host galaxies. Figure 9 shows the evolution of the iron abundance of gases in spirals (long-dashed line) and ellipticals (short-dashed line). For ellipticals, the model line is truncated at \( z = 3.05 \), where ellipticals lose their gases by the galactic wind. As the chemical enrichment in ellipticals takes place in short time, the iron abundance reaches \([\text{Fe/H}] \sim -1 \) at \( z \sim 4.3 \). Then, the metallicity effect on SNe Ia is not seen.
In spirals, the iron abundance reaches [Fe/H] $\sim -1$ later at $z \sim 2.3$, which results in the SN II break at $z_{1\alpha} \sim 2$.

For reference, the dotted line shows the cosmic chemical evolution calculated for the observed cosmic SFR. Here the correction of the dust extinction (Pettini et al. 1998) is taken into account, and the initial gas fraction is $\Omega_{g,\infty} = 3.2 \times 10^{-3} h^{-1}$. Because of the low SFR at high redshifts, the redshift where the [Fe/H] reaches $-1$ as late as $z \sim 2$ than that in spirals, and thus $z_{1\alpha} \sim 1.6$. The model in Figure 4 of Kobayashi et al. (1998) has even smaller $z_{1\alpha} (\sim 1.2)$ was not included the dust correction, and $\Omega_{g,\infty} = 2 \times 10^{-3} h^{-1}$ was adopted.

5.2. In Fields

We also predict the cosmic supernova rates for the case that the formation of ellipticals in fields are protracted, that is, the formation epoch of ellipticals spans over the wide range of redshifts. The upper panel of Figure 10 shows the cosmic SFR (solid line) as a composite of spirals (long-dashed line) and field ellipticals (short-dashed line). The SFR in spirals is the same as in the upper panel of Figure 7, but the star formation in ellipticals continues to the present on the average. The synthesized cosmic SFR is in good agreement with the observed one, except for the recent H$\alpha$ data at $z \sim 0.9$ (Glazebrook et al. 1999). The peak of the star formation appears at $z \sim 3$, which is consistent with the recent sub-mm data (Hughes et al. 1998).

The lower panel of Figure 10 shows the cosmic supernova rates (solid line) as a composite of spirals (long-dashed line) and elliptical (short-dashed line). The upper and lower three lines show the SN II and Ia rates, respectively. The SN Ia rate in spirals drops at $z_{1\alpha} \sim 2$. In contrast to Figure 7, the SN Ia rate in field ellipticals gradually decreases from $z \sim 2$ to $z \sim 3$. Although the timescale of star formation each elliptical is as short as in the lower panel of Figure 7, the star formation takes place more gradually if SFR is integrated over the ellipticals of which formation epoch distributes as Figure 4. Then the peaks of the SN Ia rate is shifted from $z \sim 3$ to $z \sim 2$ because of the lifetime of the SN Ia progenitors. Figure 11 is the same as the lower panel of Figure 10, but for the supernova rate per volume.

The rate of SNe II in ellipticals evolves following the SFR without time delay. Then, SNe II may be observed in low-redshift ellipticals. The difference SN II and Ia rates between cluster and field ellipticals reflects the difference in the star formation histories in different environments.

6. DISCUSSION

We should note that these exist several uncertainties involved in the redshift $z_{1\alpha}$ where the SN Ia rate drops.

Cosmology —– If we adopt other cosmologies $(H_0, \Omega_m, \lambda_0) = (50, 1.0, 0), (65, 0.2, 0), (65, 0.2, 0.8)$, and $(75, 0.1, 0.9)$ with $z_{1\alpha} = 5$, $z_{1\alpha}$ becomes $\sim 1.4, 1.6, 2.1$, and 2.3, respectively.

Metallicity Effect on SNe Ia —– If the metallicity effect on SNe Ia were much weaker, the delay of SN Ia occurrence would depend only on the lifetime of SNe Ia. Since the shortest lifetime is $\sim 0.5$ Gyr, many SNe Ia could be observed at $z \gtrsim 3$ in both spirals and ellipticals.

SFR in Ellipticals —– If elliptical galaxies are formed with relatively continuous star formation as suggested by the hierarchical clustering simulations, the chemical enrichment timescale is not so short, and the SN Ia rate of ellipticals drops at lower redshift because of the metallicity effect. For example, if ellipticals is assumed to grow through the star formation at a constant rate for a period of 5 Gyr, and stop the star formation at $z \sim 1$, then the SN Ia rate of ellipticals drops at $z \sim 2.5$.

7. CONCLUSIONS

In the present paper, we have made predictions of the cosmic supernova rate history as a composite of the supernova rates in different types of galaxies. We adopt the SN Ia progenitor scenario including the metallicity effect (Kobayashi et al. 1998), which successfully reproduces the chemical evolution of the solar neighborhood. To calculate the cosmic SFR, we construct the evolution models for spiral and elliptical galaxies to meet the latest observational constraints such as the present gas fractions and colors for spirals, and the mean stellar metallicity and the color evolution from the present to $z \sim 1$ for ellipticals.

Owing to the two types of the progenitor system (MS$+$WD and RG$+$WD), i.e., shorter ($0.5 - 1.5$ Gyr) and longer lifetimes ($2 - 20$ Gyr) of SN Ia progenitors, we can explain the difference in the relative ratio of the SN Ia to SN II rate $R_{\text{Ia}}/R_{\text{II}}$ between the early and late types of spirals. Owing to the over 10 Gyr lifetime of the RG$+$WD systems, SNe Ia can be seen even at present in ellipticals where the star formation has already ceased more than 10 Gyr before.

Then we construct the cosmic SFR as the composite of the SFR for different types of galaxies, and predict the cosmic supernova rates:

1. In the cluster environment, the synthesized cosmic SFR has an excess at $z \gtrsim 3$ corresponding to the SFR in ellipticals and a shallower slope from the present to the peak at $z \sim 1.4$, compared with Madan’s plot. The predicted cosmic supernova rate suggests that SNe Ia can be observed even at high redshifts because the chemical enrichment takes place so early that the metallicity is large enough to produce SNe Ia at $z \gtrsim 3$ in cluster ellipticals. In spirals the SN Ia rate drops at $z \sim 2$ because of the low-metallicity inhibition of SNe Ia.

2. In the field environment, ellipticals are assumed to form at such a wide range of redshifts as $1 \lesssim z \lesssim 4$. The synthesized cosmic SFR has a broad peak around $z \sim 3$, which are in good agreement with the observed one. The SN Ia rate is expected to be significantly low at $z \gtrsim 2$ because the SN Ia rate drops at $z \sim 2$ in spirals and gradually decreases from $z \sim 2$ in ellipticals.
C.K. thanks to the Japan Society for Promotion of Science for a financial support. This work has been supported in part by the grant-in-Aid for Scientific Research (08640336) and COE research (07CE2002) of the Ministry of Education, Science, Culture, and Sports in Japan. K.N. thanks to the participants in the workshop on “Type Ia Supernova” (Aspen Center for Physics, 13-24 June 1999) for informative discussion. We would like to thank I. Hachisu and M. Kato for providing us with their new results, and T. Kodama for providing us with the database of simple stellar population spectra.

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Nomoto, K., Iwamoto, K., Nakasato, N., Thielemann, F.-K., Brachwitz, F., Tsumoto, T., Kubo, Y., & Kishimoto, N. 1997b, Nuclear Physics, A621, 4676
Nomoto, K., Yamaoka, H., Shigeyama, T., Kumagai, S., & Tsumoto, T. 1994, in Supernovae, Les Houches Session LIV, ed. S. A. Bludman et al. (Amsterdam: North-Holland), 199
Pain, R. 1999, talk at the Type Ia Supernova workshop (Aspen Center for Physics)
### Table 1

**The input parameters.**

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Col. (1).— Galaxy type.

Col. (2)(3).— Timescales of the star formation and inflow in Gyr.

### Table 2

**The calculated quantities for spirals and ellipticals at 15 Gyr.**

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<th>$f_g$</th>
<th>$f_s$</th>
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<th>$[\text{M/H}]_s$</th>
<th>$[\text{Fe/H}]_g$</th>
<th>$[\text{Fe/H}]_s$</th>
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<th>$R_{\text{Ia}}$</th>
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Col. (1).— Galaxy type.

Col. (2)(3).— Gas and stellar fractions.

Col. (4)(6)(8).— Abundances of gas $[\text{M/H}]_g \equiv \log Z/Z_\odot$.

Col. (5)(7)(9).— Mean stellar abundances $[\text{M/H}]_s \equiv \log Z_s/Z_\odot$.

Col. (10)(11).— SN II and Ia rates per mass in $[\text{Gyr}/10^3 M_\odot]$.

Col. (12)(13).— SN II and Ia rates per luminosity in $[\text{Century}/10^{10} L_{B\odot}]$.

Col. (14)(15).— $B - V$ and $U - B$ colors.

Fig. 1.— The distribution functions of the companion mass (upper panel) and the companion lifetime (lower panel). In the lower panel, the solid and dashed lines are for $Z = 0.002$ and $Z = 0.02$ (solar), respectively. MS+WD and RG+WD denote that the companions of the white dwarfs (WD) is the somewhat evolved near main-sequence (MS) star and the red-giant (RG), respectively.
Fig. 2.— Star formation rates (SFR: top panel) gas fractions (middle panel) and $B-V$ colors (bottom panel) in four types of spirals: S0a-Sa (solid line), Sab-Sb (long-dashes line), Sbc-Sc (short-dashed line), and Scd-Sd (dotted line). The present B-V colors are taken from Roberts & Haynes (1994). We use the gas (i.e., HI+H$_2$) fractions which are normalized by the present blue luminosity of the galaxy to avoid the uncertainty in the fractions of the dark matter. The HI mass is taken from Roberts & Haynes (1994), and the H$_2$ mass is derived from the H$_2$/HI ratios (Casoli et al. 1998).
Fig. 3.— The passive color evolution of a model of cluster ellipticals up to $z \sim 1$, compared with the observational data (Stanford, Eisenhardt & Dickinson 1998).

Fig. 4.— The distribution function of the formation epoch adopted in a model of field ellipticals. The observational data are estimated from the spectra of ellipticals in the Hubble Deep Field by Franceschini et al. (1998).
Fig. 5.— The ratio of the SN Ia rate to SN II rate $R_{\text{Ia}}/R_{\text{II}}$ in spiral galaxies. The upper and lower lines show the early-type spirals S0a-Sb and late-type spirals Sbc-Sd, respectively. The solid, dashed, and dotted lines are calculated with our SN Ia model, the single delay-time model with $t_{\text{Ia}} \sim 1.5$ Gyr (Yoshii et al. 1996), and the DD model (Tutukov & Yungelson 1994), respectively. The observational data are taken from Cappellaro et al. (1997).

Fig. 6.— The SN Ia rate in elliptical galaxies. The solid, dashed, and dotted lines are calculated with our SN Ia model, the single delay-time model with $t_{\text{Ia}} \sim 1.5$ Gyr (Yoshii et al. 1996), and the DD model (Tutukov & Yungelson 1994), respectively. The observational data is taken from Cappellaro et al. (1997).
Fig. 7.— The upper panel shows the cosmic SFR (solid line) as a composite of the SFR in spirals (long-dashed line) and ellipticals (short-dashed line). The symbols are the observational data (Gallego et al. 1995, open triangle; Lilly et al. 1996, open circles; Madau et al. 1996, open squares; Connolly et al. 1997, filled circles; Tresse & Maddox 1998, open pentagon; Treyer et al. 1998, filled square; Glazebrook et al. 1999, filled pentagon; Hughes et al. 1998, star; Pettini et al. 1998, filled triangle). The lower panel shows the cosmic supernova rate (solid line) as a composite of those in spirals (long-dashed line) and ellipticals (short-dashed line). The observational data are taken from Pain et al. (1996; circle) and Pain (1999; square).
Fig. 8.— The cosmic supernova rate per volume (solid line) as a composite of those in spirals (long-dashed line) and ellipticals (short-dashed line). The observational data is taken from Pain (1999).

Fig. 9.— The evolution of the iron abundance in the gases of spirals (long-dashed line) and ellipticals (short-dashed line). For the dotted line, the observed cosmic SFR with the dust correction is adopted.
Fig. 10.— The same as Figure 7, but for ellipticals whose formation epochs span over $1 \lesssim z \lesssim 4$; this might correspond to field ellipticals.
Fig. 11.— The same as Figure 8, but for ellipticals whose formation epochs span over $1 \lesssim z \lesssim 4$; this might correspond to field ellipticals.