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Model-Synthesized Rate of Type Ia Supernovae and its Influence on the Chemical Enrichment of the ISM *

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Abstract Using Hurley's rapid binary stellar evolution code, we have studied the model-synthesized rate of Type Ia Supernovae (SNe Ia) and its influence on the chemical enrichment of the interstellar medium ejected by stellar populations. We adopt two popular scenarios, i.e., single degenerate scenario (SD) and double degenerate scenario (DD), for the progenitors of SNe Ia to calculate the rates of SNe Ia. Rates calculated in this work agree with that of Hachisu et al. and Han & Podsiadlowski, but are different from that usually adopted in chemical evolution models of galaxies. We apply the rates of SNe Ia to the chemical enrichment (especially Fe enrichment), then compare the results with previous studies. As known SNe Ia slightly affect the enrichment of C, N, O and Mg elements, while significantly affect the enrichment of Fe. We find that the occurrence and the value of the Fe enrichment in our models are earlier and smaller than that commonly adopted in chemical evolution models. We also study the evolution of [Mg/Fe] ratios, which are almost reciprocals of the Fe enrichment. The study may provide constraints on the free parameters of chemical evolution models of galaxies and evolutionary population synthesis.

Key words: galaxies: abundances — supernovae: general—galaxies: stellar content—white dwarfs

1 INTRODUCTION

Many studies have been devoted to the chemical evolution of galaxies, and considerable progress has been attained. However, in the chemical evolution models (CEMs), the treatment of Type Ia Supernovae (SNe Ia) is oversimplified. The rate of SNe Ia was included as a free parameter in order to reproduce some observational constraints such as the observed iron abundance and the evolution of α-element abundance ratio [α/Fe], without modelling in detail the evolution of progenitor systems (e.g. Greggio & Renzini 1983; Matteucci & Greggio 1986). These procedure seems to give satisfying results. SN Ia is a primary source of iron in the interstellar medium (ISM). It ejects nucleosynthesis products, and then has strong influence on the chemical evolution of ISM. It was shown that the rate of SNe Ia depends critically on the properties of the underlying binary stellar population, which means that a detailed modelling of the binary population is needed (De Donder & Vanbeveren 1998). It is essential to follow the temporal evolution of its rate as accurate as possible. Although it is generally accepted that SNe Ia arise from exploding CO white dwarfs (WD) in interacting binaries (Nomoto et al. 1997), their progenitors have not been identified (Branch et al. 1995). The uncertainties in modeling the progenitors make it difficult to predict the rate of SNe Ia. There are two popular scenarios proposed: single-degenerate scenario (SD) (Iben & Tutukov 1984; Webbink 1984; Hachisu et al. 1996, 1999, hereafter HKN96, HKNU99; Li & van den Heuvel 1997; Han & Podsiadlowski

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2004, hereafter HP04) and double degenerate scenario (DD) (Tutukov & Yungelson 1981; Iben and Tutukov 1984; Webbink 1984).

In this paper, we consider the above two possible progenitor scenarios, and attempt to calculate the model-synthesized rate of SNe Ia. For comparison, the rate of SNe Ia calculated with the prescription of Iben & Tutukov (1984, hereafter, the IT84 channel) is also given. We then study the influence of the model-synthesized SNe Ia on chemical enrichment of C, N, O, Mg and Fe of the ISM ejected by stellar populations via the rapid stellar evolution code of Hurley et al. (2000, 2002) for two metallicities: Z=0.002 and 0.02.

In Section 2, we describe the stellar population models, the adopted stellar yields and scenarios for the progenitors of SNe Ia, and give some details of the modelling algorithm. In Section 3, we give the main results and a discussion. In Section 4, we summarize and conclude.

2 MODEL

The main purpose of this paper is to construct models to check the influence of SNe Ia on the chemical yields of stellar populations.

2.1 The Chemical Evolution Model

Chemical evolution of the material ejected by stellar populations takes place as a result of stellar evolution. For simplicity, our models only consist of single stellar populations (SSPs) and the events of SNe Ia. First, we calculate the rates of SNe Ia by binary stellar populations (BSPs) for different progenitor scenarios. The masses of the SSPs and the BSPs are normalized to $1 M_\odot$, respectively. We then add the rates of SNe Ia to the SSPs by simply assuming that the rates of SNe Ia of the normalized SSPs are the same to that of the normalized BSPs. For the SSPs, we follow the evolution of each star from its initial state to the state when it becomes a compact object: a WD, a neutron star (NS) or a black hole (BH). We also assume that stars enrich the ISM only at the time when they die.

We adopt the results of core collapse simulations of Fryer (1999), i.e., stars with an initial mass more than $40\,M_\odot$ form BHs without SN explosion. Actually, it may be possible for very massive stars to contribute to the ISM via γ-ray bursts (GRBs), hypernovae, and type Ib/c supernovae. However, this does not affect our results much due to the low formation rate of massive stars.

2.2 The Stellar Yields

In this section we describe the stellar yields adopted in this work. We use the following nucleosynthesis for five chemical species: C, N, O, Mg and Fe.

Very low mass stars ($M < 0.9\,M_\odot$) do not contribute to the enrichment of the ISM, because their lifetimes are much longer than Hubble time. They only take up materials.

Low- and intermediate- mass stars ($0.9\,M_\odot \leq M \leq 8.0\,M_\odot$) contribute to the enrichment of the ISM by mass loss and planetary nebula ejection. They enrich the ISM mainly in C and N. For these stars, we adopt the stellar yields of van den Hoek & Groenewegen (1997, hereafter, VG97).

Massive stars ($M > 8\,M_\odot$) are the progenitors of Type II SNe. They enrich the ISM by hydrostatic burning and supernova explosion. They are the main producers of most of the heavy isotopes. For stars with $11\,M_\odot < M < 40\,M_\odot$, the yields of Wooseley & Weaver (1995, hereafter, WW95) are taken. For Fe-peak isotopes, we reduce the yields by a factor of two as suggested by Timmes et al. (1995). In order to reproduce the observed O/Fe ratio in halo stars, Timmes et al. (1995) suggested that the Fe yields of WW95 are probably overestimated. Otherwise, the WW95 massive stars alone can make almost the full solar abundance of Fe-peak nuclei, leaving no room for SN Ia. Taking the uncertainties in the yields into account, especially those of Fe-peak nuclei, we infer the reduction suggested by Timmes et al. (1995) reasonable. For simplicity, yields are linearly interpolated in mass. Since no reliable yields are available for 8–11 $M_\odot$ stars, we assume that their net yields are zero, i.e., the abundances of the material ejected by these stars are their initial abundances, which is a commonly adopted assumption in CEMs (e.g. Thomas et al. 1998; Goswami & Prantzos 2000; Hou et al. 2000). For our study the influence of this treatment is insignificant.

The recent yields of the W7 model of Iwamoto et al. (1999) are adopted. It is an updated version of the original W7 model of Thielemann et al. (1986), calculated for $Z = 0$ and $Z_\odot$, in which the deflagration starts in the center of an accreting WD, burns about half of the stellar material in nuclear statistical equilibrium and produces about 0.7 $M_\odot$ of ^{56}Fe (in the form of of ^{56}Ni). We just take the results of Z=0.02 as the yields of SNe Ia for the two metallicities considered in this paper.

2.3 The Progenitor of SNe Ia

Theoretically, there is a consensus that an SN Ia is the explosion and complete disintegration of a CO WD that has a mass close to the Chandrasekhar limit $M_{\rm Ch}$ (1.378 $M_\odot$ in this work). We adopt two scenarios for the progenitors of SNe Ia: the DD scenario and the optically thick wind SD scenario.

2.3.1 The DD Scenario

In DD scenario the SNe Ia arise from the merging of two close CO WDs that have a combined mass larger than or equal to $M_{\rm Ch}$ (Iben & Tutukov 1984; Webbink 1984). Both dwarfs are brought together by gravitational wave radiation (GW) on a timescale $t_{\rm GW}$ (Landau & Lifshitz 1962),

$$t_{\rm GW}({\rm yr}) = 8\times 10^7({\rm yr})\times \frac{(M_1+M_2)^{1/3}}{M_1 M_2}P^{8/3}({\rm h}), \tag{1}$$

where P is the orbital period in hours, $t_{\rm GW}$ in years and M_1, M_2 in $M_\odot$.

The time elapse from the birth of stars to the occurrence of SN Ia is equal to the sum of the timescale on which the secondary star becomes a WD and the orbital decay time $t_{\rm GW}$.

2.3.2 The SD Scenario

The SD scenario was first proposed by Whelan & Iben (1973), later on promoted and further elaborated by the Tokyo group (Nomoto et al. 1999). The progenitor binary system consists of a CO WD that accretes hydrogen from a Roche lobe filling non-degenerate companion star.

In order to increase the mass of the CO WD, hydrogen and helium must burn stably (or flash weakly) on top of the CO WD. Computations showed that these can happen if the accretion rate is in a narrow range $\dot{M}_{\rm L} < \dot{M} < \dot{M}_{\rm U}$ (Nomoto et al. 1979; Fujimoto 1982). We neglect the effect of metallicity on the accretion rate limits since its effect is small (Meng et al. 2006). We adopt the prescription used by HKNU99 for the mass growth of a CO WD by accretion of material from its companion. When the mass of the CO WD reaches the critical mass of 1.378 $M_\odot$ (Nomoto et al. 1984), an SN Ia presents.

2.4 The IT84 Channel

Widely used to estimate the rate of SNe Ia, is equation (1) of Iben & Tutukov (1984), which reads

$$\nu = 0.2\Delta q\int_{M_{\rm A}}^{M_{\rm B}}\frac{{\rm d}M}{M^{2.5}}\Delta{\rm log}A{\rm yr}^{-1}, \tag{2}$$

where ν is the rate of SNe Ia, Δq and $\Delta{\rm log}A$ denote the appropriated ranges of the initial mass ratio and the initial separation, respectively, and $M_{\rm A}$ and $M_{\rm B}$ the lower and the upper limits of the primary mass which leads to SNe Ia explosions, respectively.

We adopt the above equation to calculate the rate of SNe Ia of a stellar population, and that the prescription of HKNU99 that SNe Ia explosions occur in the ranges of $M_1 = 5.5-8.5\,M_\odot$, $M_2 = 1.8-3.4\,M_\odot$ and $\Delta{\rm log}a = 0.5$ for $Z = 0.02$.

2.5 Monte Carlo Simulation Parameters

To set up the initial stellar population for population synthesis computations, we need distributions of the properties of the stars at birth. For single stellar populations we need a distribution only for the initial mass M_0. However, we need the following distributions for binary stellar populations: (i) the initial mass function (IMF) of the primaries; (ii) the mass-ratio distribution; (iii) the distribution of orbital separations; (iv) the eccentricity distribution; (v) the lower and upper mass cut-offs $M_{\rm l}$ and $M_{\rm u}$ of the IMF; and (vi) the metallicities Z.

We adopt a simple approximation to the IMF of Miller & Scalo (1979). The primary mass is generated with the formula of Eggleton, Fitchett & Tout (1989),

$$M_1 = \frac{0.19X}{(1-X)^{0.75} + 0.032(1-X)^{0.25}}, \tag{3}$$

where X is a random variable uniformly distributed in the range [0,1], and M_1 is the primary mass from $0.1\,M_\odot$ to $100.0\,M_\odot$.

The mass ratio q of secondary to primary is very important for the evolution of binary systems. However, its distribution is quite uncertain since the observed q-distribution is strongly affected by selection effects. We take a constant mass-ratio distribution (Mazeh et al. 1992; Goldberg & Mazeh 1994) in this work.

The distribution of separations is taken to be constant in log$a$ for wide binaries and falls off smoothly at close separations, where a is the separation:

$$an(a) = \begin{cases} \alpha_{\rm sep}(\frac{a}{a_0})^m & a \le a_0\,, \\ \alpha_{\rm sep} & a_0 < a < a_1\,, \end{cases} \tag{4}$$

where $\alpha_{\rm sep}$ ≈0.070, $a_0 = 10R_\odot$, $a_1 = 5.75 \times 10^6 R_\odot = 0.13\,$pc and $m \approx 1.2$. This distribution implies that there is an equal number of wide binary systems per logarithmic interval, and that approximately 50 percent of stellar systems are binary systems with orbital periods less than 100 yr (Han et al. 1995).

The orbits of semidetached binaries are generally circularized by tidal force on a timescale which is much smaller than the nuclear timescale. Also during stable Roche lobe overflow (RLOF) a binary is expected to become circularized. Therefore we take e_0 = 0. Also, we use the rapid evolution code of Hurley et al. (2000, 2002) to evolve the populations of stars.

3 RESULTS AND DISCUSSION

3.1 The Birthrate of SNe Ia

We present the time evolution of SNe Ia rates for the SD scenario and the DD scenario after an instantaneous starburst for two metallicities (Z=0.002 and 0.02). These calculations give the delay time of the SNe Ia events and the delay time determines the onset of SNe Ia iron enrichment. We take 1×10^7 binary systems for each metallicity, in which the masses of primaries and secondaries are between $0.1\,M_\odot$ and $100.0M_\odot$. For comparison, we normalize the total mass of the starburst to $10^{11}\,M_\odot$ in this subsection. We then compute the resulting birth rates of SNe Ia for the SD scenario and the DD scenario, respectively.

Figure 1 shows the time evolution of birth rates of SNe Ia for a single starburst of $10^{11}\,M_\odot$ for the two metallicities in the cases of different progenitor scenarios. From Figure 1 we can see that the birth rate from the IT84 channel is the biggest, while the birth rate from the SD scenario is the smallest, because of IT84's large parameter space. We also see that the occurrence of SNe Ia for the IT84 channel starts latest, and the lasting time is the shortest. In this channel, if the initial parameters of stars are in the appropriate ranges, we treat it as single stars. We simply assume that an SN presents when the secondary ends its main sequence evolution. The occurrence of SNe Ia for the SD and DD scenarios start almost at the same time, but ends much later for the DD scenario, due to its long timescale of GW. Panel (a) of Figure 1 shows that the peak value of the rate of SNe Ia for Z=0.002 is earlier than that of Z=0.02. The reason is that stars with lower metallicity evolve faster. For metallicity lower than 0.002, the optical stellar wind model may be invalid (Kobayashi et al. 1998). Most of the supernova explosions occur between 0.07 and 0.9 Gyr after the burst, which is earlier than that of HKNU99 and HP04. Panel (b) of Figure 1 shows that the difference of the rates for the DD scenario among different metallicites is small. It shows that the rate depends primarily on the common envelope ejection efficiency $\alpha_{\rm CE}$. Lowering the efficiency reduces the rate since most progenitor systems evolve through CE phases and the orbital shrinkage prevents the formation of double WDs system. A high $\alpha_{\rm CE}$ leads to higher birth rates of SNe Ia for all metallicities, in agreement with the results of Yungelson et al. (1994) and Han (1998).

Using the SD scenario, HKNU99 and HP04 calculated the birth rate of the SNe Ia for a starburst of $10^{11}\,M_\odot$ of solar metallicity. Li & van de Heuvel (1997) also estimated the rate of SNe Ia in the Galaxy. They found that the birth rate was smaller than that from observations. Our results are similar to theirs for

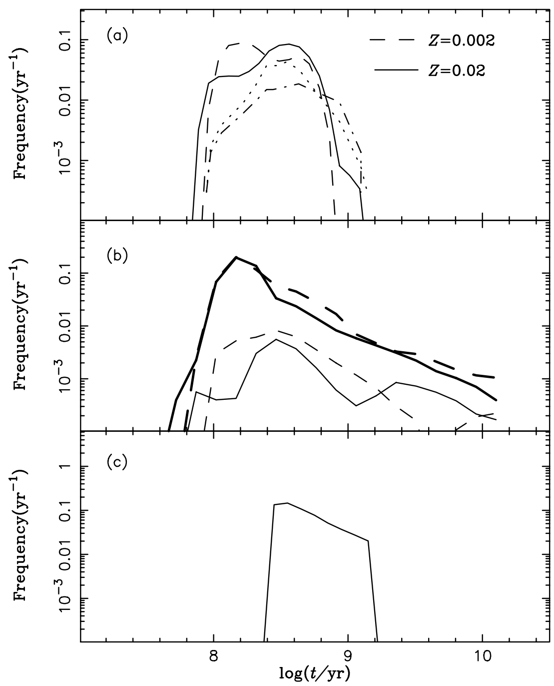

Fig. 1 Time evolution of birth rates of SNe Ia for a single starburst of 10^{11} $M_\odot$ for metallicities of Z=0.002 and 0.02. The computations are made separately for the SD scenario, the DD scenario and the IT84 channel. Dashed and solid curves are for Z=0.002 and 0.02, respectively. Panel (a) shows for the SD scenario. Dotted and dash-dotted curves are the results of HKNU99 and HP04, respectively. Panel (b) is for the DD scenario with different efficiencies of CE ejection. Thick and thin curves are for $\alpha_{\rm CE} = 3.0$ and $\alpha_{\rm CE} = 1.0$, respectively. Panel (c) is for the IT84 channel.

the same metallicity. Panel (a) of Figure 1 gives a comparison of the rate of our simulation Z=0.02 to that of HKNU99 and HP04. The rate based on the simulation agrees with the results of HKNU99 and HP04, but it is slightly greater than those in the range 0.07–0.14 Gyr. The reason is that we just assume the mass transfer of the secondary occurs on a thermal timescale, this makes some systems experience supernova explosion in our simultion, but it is not the case in HKNU99 and HP04.

Recently, several kinds of SNe Ia have been detected, such as SN 2002ic, SN 2002cx, but the rates are very small (Han & Podsiadlowski 2006; Prieto et al. 2007).

3.2 The Chemical Evolution of the ISM Ejected by Stellar Populations

We evolve populations of single stars from zero-age main sequence to an age of 12 Gyr. The amount of C, N, O, Mg and Fe elements ejected by the stellar populations of Z=0.002 and 0.02 with and without the influence of SNe Ia is computed. To easily scale our results to any starburst of arbitrarily total stellar mass, we normalize the total mass of the starburst to $1 M_\odot$ in this subsection.

Figure 2 shows that the enrichment of C, N, O and Mg elements depends slightly on the SNe Ia. This is because that SNe Ia are rare and the yields of these elements of SNe Ia are small. The figure also shows that there is a time delay of at least 5 Myr between the birth and release of ejecta by stars.

Figure 3 shows that SNe Ia have important influence on the enrichment of Fe. The ejected Fe mass is large, about 0.7 $M_\odot$ per SNe Ia. Different scenarios make Fe enrich differently. The SNe Ia of IT84 channel starts earliest to influence the Fe enrichment, and ends its influence earliest, so its lasting influence time is the shortest. The SNe Ia of the SD scenario and the DD scenario start influence almost at the same time, but the SNe Ia of the DD scenario ends much later, due to its long GW timescale, as that in Figure 1.

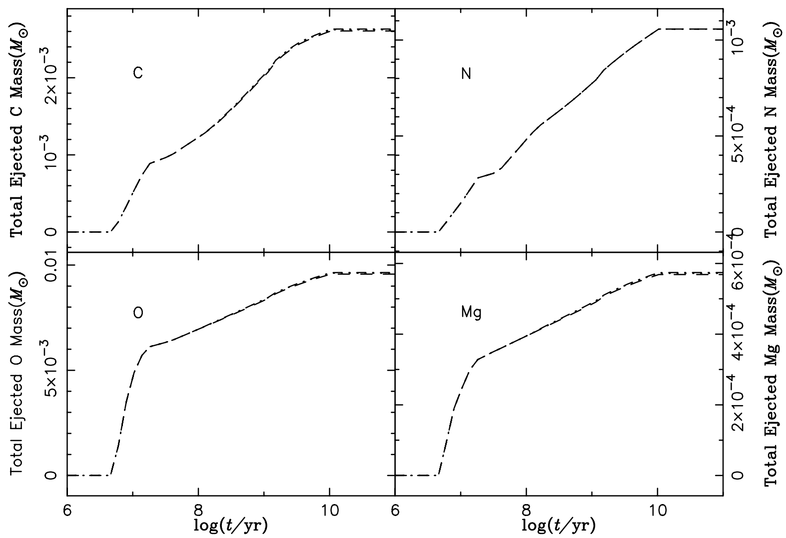

Fig. 2 Chemical evolution of C, N, O and Mg elements for stellar populations of $Z = 0.02$ for different scenarios of progenitor of SNe Ia. Dashed, dash-doted and dotted curves are for the case without the influence of SNe Ia, for the SD scenario and for the DD scenario, respectively.

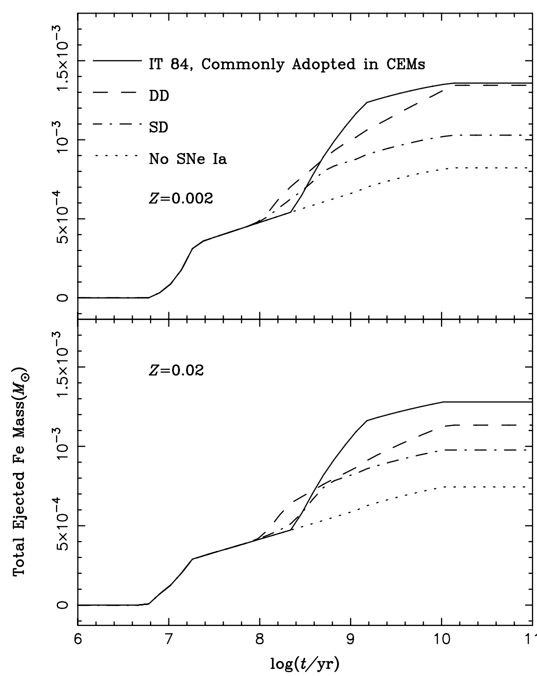

Fig. 3 Chemical evolution of Fe element of stellar populations for metallicities of Z=0.002 and 0.02 for different scenarios of the progenitor of SNe Ia. Solid, dashed, dash-dotted and dotted curves are for the case of IT84 channel, the DD scenario, the SD scenario and the case without any influence of SNe Ia, respectively.

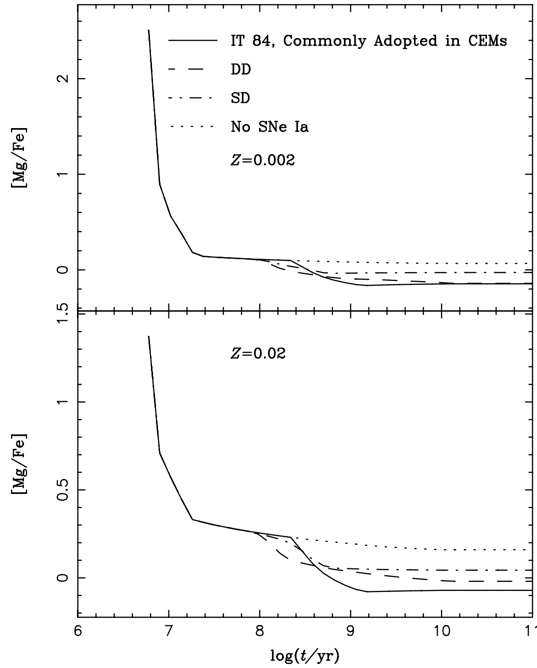

Fig. 4 Similar to Fig.3 but for [Mg/Fe]. Note that solid curves are from the IT84 channel which is commonly adopted in CEMs.

Figure 4 shows the time evolution of [Mg/Fe] ratios of ISM of stellar populations with different metallicities for different progenitors. They are almost reciprocals of the Fe enrichment, because SNe Ia slightly influence the Mg enrichment. Different [Mg/Fe] ratios may have some important influence on the evolution of the next generation stars: stars with high [Mg/Fe] ratio will evolve faster. This may affect the results of evolutionary population synthesis.

In the chemical evolution models of galaxies, there were several free parameters, whose values have been taken to optimize the observations best. Our study may provide some constraints on these free parameters.

4 CONCLUSIONS

In summary we have obtained the following conclusions:

1. The rate of SNe Ia calculated by IT84 channel is significantly different from that of our simulations.
2. For the SD scenario, the rate of SNe Ia in this paper agrees with those of HKNU99 and HP04 for solar metallicity. Lowering metallicity would lead to a smaller timescale for the production of SNe Ia.
3. For the DD scenario, the rate of SNe Ia is about 3 times greater than that for the SD scenario, and a high $\alpha_{\rm CE}$ leads to higher birth rates for all metallicities. The rates of SNe Ia for this scenario are only slightly influenced by metallicity.
4. The enrichment of C, N, O and Mg elements depends slightly on the rate of SNe Ia, while the enrichment of Fe depends strongly on the rate, which agrees with previous studies. Different progenitors of SNe Ia influence the occurrence and lasting time and the extent of Fe enrichment largely.
5. The [Mg/Fe] ratio of the ISM is greatly influenced by different rates of SNe Ia from different progenitors. This may have some important effects on the next generation stars and may make stellar populations bluer.

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