DORMANT DWARF SPHEROIDAL GALAXIES, DEACTIVATED BY TYPE Ia SUPERNOVAE

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ABSTRACT

Some dwarf spheroidal galaxies have experienced periods many Gyr long without star formation. We show that Type Ia supernovae, formed from a first generation of stars, can delay a second epoch of star formation by several Gyr, if the total gas mass in the dwarf spheroidals is smaller than $10^8 M_\odot$. The details depend on the assumed Type Ia supernova model and the mass fraction of stars formed in the first population. This scenario requires that dwarf spheroidals be confined by dark matter halos, since otherwise the heated gas would be lost due to tidal effects and galactic winds. If Type Ia supernovae play an important role, heating the gas in dwarf spheroidals, they should also increase their iron abundance during the epoch without star formation. The subsequent stellar generation should then start with a higher [Fe/H] than that of the most iron-rich stars found in the previous generation.

Subject headings: supernovae: general — white dwarfs

1. INTRODUCTION

The color-magnitude diagrams of dwarf spheroidal galaxies (dSph's) have revealed an unexpectedly complex star formation history. The Carina dSph, for example, experienced an early epoch of star formation 11–13 Gyr ago, followed by a period without detectable star formation activity. A second star formation epoch started about 5–8 Gyr ago (Mighell & Butcher 1992; Smcker-Hane et al. 1996). Periods of inactivity several Gyr long have also been found in other satellite systems of the Milky Way, like Carina (Mighell 1990), or in the recently discovered dwarf spheroidal galaxy in Sagittarius (Ibata, Gilmore, & Irwin 1994; Mateo et al. 1995).

These observations are quite puzzling from a theoretical point of view, since all timescales associated with processes that are considered to regulate star formation are smaller than $10^7$ yr. For example, a few times $10^7$ yr after the end of the first star formation epoch, heating by high-mass stars and Type II supernovae stopped. If the hot gas was still gravitationally bound, it could cool and fall back into the inner regions of the galaxy. The cooling and dynamical contraction timescales are of order $10^4–10^5$ yr. One therefore would expect that new molecular clouds and another generation of stars could form a few times $10^8$ yr after the end of the previous star formation epoch.

Star formation could have been delayed for a longer time, if the gas had enough angular momentum in order to form a rotationally supported H II disk. For H II column densities below a critical value, the disk could remain gravitationally stable for quite a long time and would not be able to fragment into dense molecular clouds (Gallagher & Hunter 1984; Wang & Silk 1994). The stellar components of the dSph's, however, do not show enough rotation in order to support such a scenario.

Because the dSph's are tidally limited satellite systems, it is also very unlikely that the subsequent star formation epochs were caused by late infall of new gas, several Gyr after star formation had stopped in the systems. One rather would expect that the systems lost part of their interstellar medium as a result of tidal stripping, instead of accreting gas that was originally beyond their tidal radii.

In this paper we propose a new scenario, which could explain the long periods of dormancy in dSph’s: heating by Type Ia supernovae (SNe Ia). SNe Ia are considered to result from explosions of white dwarfs (WDs), which occur several times $10^8–10^9$ yr after the formation of their progenitors. If the rate of explosions was high enough, radiative cooling of the hot interstellar medium, and the formation of giant molecular clouds, could have been delayed as a result of the energy input through SNe Ia. SNe Ia could then suppress star formation for several Gyr.

2. TYPE Ia SUPERNOVA SCENARIOS

SNe Ia are assumed to result from the explosions of CO WDs in close binary systems. Different scenarios have been proposed.

In the double degenerate (DD) scenario (Iben & Tutukov 1984), two CO WDs merge by the emission of gravitational wave radiation. The explosion occurs due to C ignition at the center, when the more massive WD, after tidal disruption of the less massive WD, has accreted enough material to reach the Chandrasekhar mass.

In the case of symbiotic systems (SSs) (Munari & Renzini 1992; Kenyon et al. 1993) a CO WD accretes material from the low-velocity wind of a red giant. The WD can explode, with a mass still lower than the Chandrasekhar mass, when C detonation is induced by the previous detonation of He, accumulated at the surface from burning of previously accreted hydrogen.

Another class of candidate systems are cataclysmic-like systems (CLSs), where a CO WD accretes hydrogen on a thermal timescale from a Roche lobe filling main-sequence or subgiant companion (Iben & Tutukov 1984; Canal, Ruiz-Lapuente, & Burkert 1996). Those systems have also been named, in the SNe Ia context, “H Algols” (Branch et al. 1995).

Figure 1 shows the expected time evolution of the SN Ia rates $\dot{\gamma}_{SN,Ia}$ normalized to the total mass of the stellar system, for the SS, CLS, and DD scenarios. It is assumed that a stellar system with mass $M_*$ formed, with a constant star formation rate $SFR = M_*\dot{\gamma}_{SF}$ and a star formation timescale $\tau_{SF}$ of $10^5$ yr. Varying $\tau_{SF}$ between $5 \times 10^5$ and $2 \times 10^6$ yr does not change the normalized SN Ia rates.

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significantly. For the DD and CLS scenarios, the SN Ia rates depend on the common envelope parameter $\alpha$, a quantity of order unity, which measures the efficiency by which orbital energy is deposited into the ejection of a common envelope (Iben & Tutukov 1984). For the DD scenario we show rates for $\alpha = 1$ and $\alpha = 0.3$ and for different mass ratio ($q$) distributions of the components of the binary system. The rate for the SS scenario has been computed adopting an efficiency $\eta_{SS} = 1$ in producing explosions (Ruiz-Lapuente, Burkert, & Canal 1995), which is an absolute upper limit, and then lowering this efficiency down to $\eta_{SS} = 0.01$. Probable values should be closer to 0.1. Note that in this scenario $\nu_{SN Ia}$ scales linearly with $\eta_{SS}$. For the CLS scenario (WD growing to the Chandrasekhar mass) the rates depend on the adopted upper limits of the mass accretion rate for He detonation and on the conditions for the stability of mass accretion onto the white dwarf.

3. THE DWARF GALAXY MODEL

More than 10 Gyr ago the initially completely gaseous proto-dSph experienced its first star formation epoch. Observations indicate that this event lasted of order $\sim 10^8$–$2 \times 10^9$ yr (for a summary see, e.g., van den Bergh 1994). During this epoch a stellar system with a mass of 20%–60% of the total final stellar mass of the dSph formed, that is, with a mass in between $2 \times 10^6$ and $10^9 M_\odot$. Its high-mass stars ionized and destroyed the molecular gas clouds, forming a hot gaseous component.

Dwarf spheroidals have low metallicities, which indicates that these systems must have lost a large fraction of their metals and gas due to tidal stripping and/or through galactic winds. For example, in order to produce a stellar system with $[\text{Fe/H}] \approx -2$, only 1% of the gas could turn into stars in the case of instantaneous recycling and efficient mixing of metals into the different gas phases, with the rest being blown out of the system. In this case, the dSph’s originally contained gas with a much larger total mass, of order $2 \times 10^7$–$10^8 M_\odot$. Note that the required gas mass was smaller in the likely event of inefficient mixing of metals between the hot and cold gas phases (Burkert, Theis, & Hensler 1993; Vater 1986, 1987). As it is preferentially the hot, metal-rich gas phase which is lost in galactic winds, a large fraction of the metals could have been lost without losing much of the gas. In this case, the total mass of the gas was more likely of order $5 \times 10^7$–$10^8 M_\odot$.

At the end of the star formation event a hot gaseous bubble had formed. If heating had been too efficient, the galaxy would have lost all of its gas and no second star formation epoch could have occurred. In the cases we are interested in, some fraction of the hot interstellar medium remained gravitationally bound. Dwarf spheroidals have large mass-to-light ratios, indicating the presence of a surrounding dark matter (DM) halo. The DM potential $\Phi_{DM}$ could have played an important role in keeping the gas bound.

$\Phi_{DM}$ is determined using recent observations, which indicate that the DM halos around dwarf galaxies represent a one-parameter family with a universal density profile $\rho_{DM}$, which can be well fitted by the following formula (Burkert 1995):

$$\rho_{DM}(r) = \frac{\rho_{DM}(0)r^3}{(r + r_0)(r^2 + r_0^2)}.$$  

(1)

The central DM density $\rho_{DM}(0)$ and the DM scale radius $r_0$ are functions of the total DM mass $M_{DM}$, which lies inside $r_0$ (Burkert 1996):

$$\rho_{DM}(0) = 4.74 \times 10^{-2} \left( \frac{M_{DM}}{10^7 M_\odot} \right)^{-2/7} M_\odot \text{ pc}^{-3},$$  

$$r_0 = 0.43 \left( \frac{M_{DM}}{10^7 M_\odot} \right)^{3/7} \text{ kpc}. $$  

(2)

Note that for typical values of $M_{DM}$ in the range $10^8$–$10^{10} M_\odot$, the dynamical timescales for radii $r \leq r_0$ are in the range $6.2 \times 10^7$–$1.2 \times 10^8$ yr, respectively. Because of their high mass-to-light ratios and the fact that the hot gas was in an extended, low-density state, we can also assume that the total gravitational potential $\Phi(r)$ of the dSph was dominated by its DM component: $\Phi(r) \approx \Phi_{DM}(r)$. $\Phi$ can then be determined from equation (1), using Poisson’s equation.

After the end of the first star formation epoch, heating by high-mass stars and Type II supernovae stopped and the bound, hot gas fraction began to cool and fall back into the central regions again, leading eventually to a second epoch of star formation. If, however, by that time the SN Ia rate
had increased sufficiently, in order to prevent the formation of cold molecular clouds the gas would have settled into a hot, hydrostatic equilibrium state, where the rate of energy loss through cooling was balanced by the rate of energy input through SNe Ia. The next epoch of star formation would have then been delayed by several Gyr.

The real situation could have been much more complex, given the fact that most SNe Ia exploded in the inner region, where star formation had occurred initially. Heating of the inner region of a gas sphere by SNe Ia could induce large-scale turbulent motions, with hot gas moving outward and cooler gas falling back into the center.

McKee & Ostriker (1977) demonstrate that frequent supernova explosions could produce a multi-component interstellar medium if the expanding remnants overlap prior to their breakup. In this case, most of the interstellar medium is swept up into a network of cold, dense shells and clouds which are embedded in a hot, tenuous intercloud medium. Star formation is likely to continue under these circumstances, even if the supernova rate is high. Adopting McKee & Ostriker’s expression for the probability $Q_{SNR}$ that supernova remnants overlap, we find for a typical proto-dSph with average gas density $n_g = 0.1 \, \text{cm}^{-3}$, gas temperature $T \approx 10^4 \, \text{K}$, and SN Ia rate $n_{SN, Ia} \approx 10^{-6} \, \text{yr}^{-1}$ that $Q_{SNR} \approx 0.02$. Type Ia supernova remnants in dwarf spheroidals will in general not overlap. They expand as isolated shells into a homogeneous, gaseous environment until their radial velocities have become of the order of the external sound speed, at which point they are dispersed. The resulting low-density cavity is later on filled again by the inflow of the surrounding gas. SNe Ia therefore act mainly as local heating sources that keep the gas in the dSph’s from cooling and condensing into molecular clouds as long as the SN Ia rate is large enough.

Detailed three-dimensional hydrodynamical simulations of the processes mentioned above are beyond the scope of this paper. As a first approximation, we neglect radial temperature gradients and turbulent flows and assume that the average gas temperature $T$ changed only on long timescales due to the global variation in the balance between heating and cooling. Given the gas temperature $T$ and assuming no significant radial temperature gradient, the gas density distribution can be determined by integrating the hydrostatic equation:

$$\rho_g(r) = \rho_g(0) \exp \left[ \frac{\Phi(r = 0) - \Phi(r)}{c^2} \right],$$

where $c = (R_g T/\mu)^{1/2}$ is the sound velocity of the gas, $R_g$ is the gas constant, and $\mu = 0.64$ is the mean molecular weight for a hot, low-metallicity gas. The central gas density $\rho_g(0)$ is determined by the known total gas mass $M_g$.

There exists a critical temperature $T_{crit}$ beyond which the gas is not confined to the dark matter halo. In this case, equation (3) has no solution for finite $M_g$ and nonzero $\rho_g(0)$. At this critical temperature the hydrostatic assumption breaks down and the system loses its gas in a galactic wind. For DM masses $M_{DM}$ of $10^8$ and $10^{10} \, M_\odot$ the critical temperatures are $2.6 \times 10^4$ and $10^5 \, \text{K}$, respectively. In order for the gas sphere not to condense efficiently into molecular clouds, its temperature must exceed $6 \times 10^3 \, \text{K}$ (see § 4). This constraint and the requirement that the gas should remain gravitationally bound leads to a lower limit for the dark matter mass of $M_{DM} \approx 10^8 \, M_\odot$.

## 4. Equilibrium States

In thermal equilibrium the gas temperature is determined by the balance between thermal energy input $(dE/dt)_{SN, Ia}$ due to SN Ia explosions and radiative cooling $(dE/dt)_{cool}$. The energy input rate is

$$\left( \frac{dE}{dt} \right)_{SN, Ia} = \eta_{SN, Ia} M_\star E_{SN} ,$$

where $\eta_{SN, Ia}$ is shown for the SS, DD, and CLS scenarios in Figure 1, $M_\star$ is the total mass of the stellar system, $\eta \approx 0.25$ (Thorton, Truran, & Janka 1996) is the efficiency factor with which a SN Ia explosion heats the surrounding interstellar medium, and $E_{SN} \approx 10^{51} \, \text{ergs}$ is the total energy released in a SN Ia explosion.

The energy loss due to radiative cooling is

$$\left( \frac{dE}{dt} \right)_{cool} = \lambda(T) \int_0^\infty n_H^2 d^3r ,$$

where $n_H$ is the local hydrogen number density of the gas, which is determined using equation (3) and $\lambda(T) = \Lambda n_H$ is the cooling rate coefficient in ergs cm$^{-3}$ s$^{-1}$ for a low-metallicity plasma.

The coefficient $\lambda$ has a temperature dependence, which makes a thermal equilibrium state possible only for gas temperatures $T \approx 10^4 \, \text{K}$, where $\lambda$ is fast increasing with increasing temperature. For an optically thin, low-metallicity plasma in ionization equilibrium, $\lambda$ reaches a maximum $\lambda_{max} = 8 \times 10^{-21} \, \text{ergs cm}^{-3} \, \text{s}^{-1}$ at $T = 1.8 \times 10^4 \, \text{K}$ and decreases again for higher temperatures (Fall & Rees 1985). If energy input due to SNe Ia increases the gas temperature beyond $T_{max}$, radiative cooling becomes less efficient whereas the SN Ia rate is not affected. The gas will be heated to even higher temperatures until the critical temperature is reached and the gas is lost.

Low-metallicity gas in ionization equilibrium is very inefficient in radiative cooling below $10^4 \, \text{K}$. It therefore seems at first as if for even very low SN Ia rates one should always expect to find a thermal equilibrium state with $T < 10^4 \, \text{K}$. Note, however, that SNe Ia drive shocks into the surrounding interstellar medium. Shocks are also expected to form in the turbulent flow that might arise due to central SN Ia heating. Shapiro & Kang (1987) demonstrate that under these circumstances and for temperatures $T < T_{min}$ molecular clouds will form efficiently, which ends the quiescent phase without star formation. According to Shapiro & Kang (1987), the cooling coefficient at $T_{min}$ is $\lambda_{min} \approx 10^{-26} \, \text{ergs cm}^{-3} \, \text{s}^{-1}$.

In summary, thermal equilibrium is expected only in a limited temperature range $6 \times 10^3 \, \text{K} \leq T \leq 1.8 \times 10^4 \, \text{K}$, where the cooling coefficient rises by almost 6 orders of magnitude from $\lambda_{min}$ to $\lambda_{max}$. If the SN Ia rate were so small that thermal equilibrium requires $\lambda < \lambda_{min}$, new molecular clouds would form. In the opposite extreme case of a very high SN Ia rate, thermal equilibrium would require $\lambda > \lambda_{max}$. Then the dwarf galaxy loses its gas. In the following we will use these constraints on $\lambda$ in order to estimate whether and how long SNe Ia could delay star formation in dSph’s.

## 5. Star Formation Delayed by Type Ia Supernovae

Can SNe Ia heat the gas so efficiently that it is lost? Following the arguments that were presented above, this
would require

\[ \lambda = \frac{\eta E_{\text{SN}} v M_g}{\int_0^\infty n_t^2 \, dr} \geq \lambda_{\text{max}} = 8 \times 10^{-21} \text{ ergs cm}^3 \text{ s}^{-1}. \]  

(6)

Numerical integrations, using equation (3) for \( n_t \) and adopting DM masses \( M_{\text{DM}} \leq 10^{10} M_\odot \) and gas temperatures \( T \leq 7 \times 10^4 \text{ K} \) (the critical temperature for a DM halo with \( M_{\text{DM}} = 10^{10} M_\odot \)), show that under these conditions \( \int_0^\infty n_t^2 \, dr \geq 2 \times 10^{10} (M_g/M_\odot)^2 \text{ cm}^{-3} \). According to Figure 1, the normalized SN Ia rates for SS, DD, and CLS scenarios never exceed a maximum value of \( 10^{-12} \text{ yr}^{-1} M_\odot^{-1} \) even when the efficiency parameters \( \eta_{\text{SS}} \) and \( \lambda \) are varied in the expected ranges. This result is true, even for combinations of the different SN Ia scenarios. Inserting these limits in equation (6), using the constraint \( M_g \leq M_g \) and assuming \( \eta = 0.25 \) and \( E_{\text{SN}} = 10^{51} \text{ ergs} \), we find that SNe Ia would only be able to produce strong galactic winds for \( M_g \leq 3 \times 10^4 M_\odot \), which is far below the expected values for the total gas mass in the dSph's. We therefore conclude that SNe Ia were never efficient enough to expel the interstellar medium in dSph's.

Star formation will start again as soon as \( \lambda < \lambda_{\text{min}} \), with \( \lambda \) being determined by equation (6). This constraint leads to a minimum SN Ia rate \( v_{\text{SN Ia, min}} \) which is required to keep the gas hot:

\[ v_{\text{SN Ia, min}} = \frac{\lambda_{\text{min}} \int_0^\infty n_t^2 \, dr}{\eta E_{\text{SN}} M_g}. \]  

(7)

The integral in equation (7) is calculated for \( T = T_{\text{min}} \) using equation (3). Assuming again \( E_{\text{SN}} = 10^{51} \text{ ergs} \), \( \eta = 0.25 \), and \( \lambda_{\text{min}} = 10^{-26} \text{ ergs cm}^3 \text{ s}^{-1} \), we find

\[ v_{\text{SN Ia, min}} = 5.16 \times 10^{-21} f \left( \frac{M_g}{M_\odot} \right)^2 \left( \frac{M_g}{M_\odot} \right) \text{ yr}^{-1} M_\odot^{-1}. \]  

(8)

The parameter \( f \) is only a function of the mass of the dark matter halo. It increases from \( f = 0.6 \) for \( M_{\text{DM}} = 10^{10} M_\odot \) to \( f = 1.3 \) for \( M_{\text{DM}} = 10^9 M_\odot \) and \( f = 1.6 \) for \( M_{\text{DM}} = 5 \times 10^8 M_\odot \). \( M_g \) represents the amount of gas which, after the previous starburst, remains gravitationally bound. \( M_\odot \) is the mass of the stellar system that provides the SNe Ia. As typical values for dSph's we adopt \( M_{\text{DM}} = 5 \times 10^{9} - 10^9 M_\odot \), \( M_g = 2 \times 10^5 - 10^6 M_\odot \), and \( M_\odot = 10 \times M_\odot \) (see § 3).
Note that it is very difficult to determine the total dark matter mass in dwarf spheroidals from the observed properties of their stellar components, as the scale radius of the visible component is likely to be much smaller than the radius of the dark matter halo.

Using the rates of Figure 1 and the constraint $v_{SN, Ia} > v_{SN, Ia, min}$, the timescale $t$ by which star formation is delayed due to SN Ia explosions can be determined. Figure 2 shows $t$ for the SS (Fig. 2a), DD (Fig. 2b), and DD + CLS (Fig. 2c) scenarios. The efficiency parameters were set to $\alpha = 1$ and $\eta_{SS} = 1$. The shaded regions indicate the regimes of heating timescales for different $M_* / M_*$, with $M_*$ varying between $2 \times 10^5$ and $10^6 M_\odot$. For this mass range, SNe Ia can indeed delay star formation by several Gyr, if the mass fraction of gas to stars is smaller than 30%.

SNe Ia, resulting from symbiotic systems, are most effective in heating dSph's. They could in principle delay star formation for more than 10 Gyr. For the SS scenario, however, the rate $v_{SN, Ia}$ depends strongly on the efficiency $\eta_{SS}$. Decreasing $\eta_{SS}$ shifts the curves of Figure 2a by the same factor to smaller $M_* / M_*$*. This effect leads to inefficient SN Ia heating for the case $\eta_{SS} \lesssim 0.2$. For example, assuming $\eta_{SS} = 0.1$, a value $t = 4$ Gyr for $M_* = 10^6 M_\odot$ requires a very small ratio $M_* / M_* \approx 2$. If the rates of Yungelson et al. (1995) are adopted, SSs never would be important in heating dSph's.

Double degenerate systems produce SNe Ia at lower rates and delay star formation only for a few Gyr. In addition, for $t > 1$ Gyr, the gas-to-star ratio must be rather small. Adopting a common envelope parameter $\alpha = 0.3$, instead of $\alpha = 1$, shifts the curves by approximately 1 Gyr to larger delay timescales. The effect of assuming a distribution of mass ratios in the progenitor systems (Mazeh et al. 1992) flatter than the Duquennoy & Mayor (1991) distribution is to increase the rates of the SNe Ia from this scenario and produce delays in star formation which are 0.5–1 Gyr longer.

For an initial star formation epoch, which lasted $\sim 1$ Gyr, cataclysmic-like systems do not produce enough SNe Ia at the end of the star formation phase to prevent the gas from cooling. The systems explode more than 1 Gyr later. By this time the gas would have cooled and condensed into stars again. Lowering the upper limit for the accretion rate leading to He detonation moves the peak in $v_{SN, Ia}$ to earlier times. For $M = 2.5 \times 10^{-8} M_\odot$ yr$^{-1}$ the CLS supernovae could delay star formation by approximately 4 Gyr. If the most restrictive conditions for the stability of mass accretion in the WD are assumed, the delay timescale is $\sim 1$ Gyr. Increasing the period of star formation to 2 Gyr allows the cataclysmic-like systems to evolve enough to produce a high SN Ia rate at the end of the star formation epoch. In this case, the SNe Ia rate from CLSs is always large as compared to the rate of supernovae resulting from DDs, and CLS supernovae alone can delay star formation by 4–5 Gyr.

Combining the CLS and DD scenarios, early energy input is provided by the SNe Ia from DD. After 1 Gyr, the SNe Ia from CLSs begin to dominate and delay star formation further by 3–4 Gyr. The DD + CLS supernovae therefore induce periods without star formation which are in general of order 4–5 Gyr, independent of $M_* / M_*$ or $M_*$. In Figure 2d the total baryonic mass $M_{tot} = M_* + M_*$ during the period of star formation inactivity is shown for systems with a period of quiescence of $t = 4$ Gyr. In the extreme case of low $M_* / M_* \approx 1$, SNe Ia could delay star formation in systems with baryonic masses as high as $M_{tot} = 1.6 \times 10^9 M_\odot$.

6. SUMMARY AND CONCLUSIONS

It has been shown that SNe Ia could suppress star formation in dSph's for several Gyr. Our calculations lead to heating timescales which are in agreement with the observations. The details depend on the total amount of gas and stars in the system and on the adopted SN Ia scenario. If the total baryonic mass exceeds $1.6 \times 10^8 M_\odot$, heating by SNe Ia becomes inefficient for $M_* > M_*$. Only in low-mass dwarf spheroidals will the star formation history be strongly affected by SNe Ia.

Three-dimensional hydrodynamical calculations are required, in order to understand in greater detail the impact of SN Ia explosions on the interstellar medium. The estimates which have been presented in this paper indicate that SNe Ia can keep the gas in dSph's at temperatures of the order of $10^4$ K for several Gyr and affect significantly the internal dynamical evolution of the gaseous components in those galaxies. SNe Ia, however, do not provide enough energy to expel a substantial fraction of the baryonic component in a strong galactic wind.

During the epoch without star formation, SNe Ia continuously inject iron into the interstellar medium, increasing its iron abundance. Any subsequent generation of stars that forms from that gas should therefore start with a higher [Fe/H] than the most iron-rich stars of the population that formed prior to the period of inactivity. Of order 0.6 $M_\odot$ of iron are produced per SN Ia event. A stellar system with mass $M_* = 5 \times 10^3 M_\odot$ could then enrich primordial gas with a total mass of $10^7 M_\odot$ over $3 \times 10^9$ yr to [Fe/H] = $-1.4$ for the SS scenario if the upper limit $\eta_{SS} = 1$ is adopted and to [Fe/H] = $-1.9$ for the DD + CLS scenario, provided that no iron-rich gas is lost. A comparison of the observed iron abundance in the younger stellar generation with respect to the older population could provide important information about the efficiency with which SNe Ia heated and enriched the dwarf spheroidals during their long periods of dormancy.

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