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THE TYPE Ia SUPERNOVA RATE

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ABSTRACT

We explore the idea that the Type Ia supernova (SN Ia) rate consists of two components: a prompt piece that is proportional to the star formation rate (SFR), and an extended piece that is proportional to the total stellar mass. We fit the parameters of this model to the local observations by Mannucci and collaborators and then study its impact on three important problems. On cosmic scales, the model reproduces the observed SN Ia rate density below $z = 1$ and predicts that it will track the measured SFR density at higher redshift, reaching a value of $(1–3.5) \times 10^{-4}$ yr^{-1} Mpc^{-3} at $z = 2$. In galaxy clusters, a large prompt contribution helps explain the Fe content of the intracluster medium. Within the Galaxy, the model reproduces the observed stellar [O/Fe] abundance ratios if we allow a short (≈0.7 Gyr) delay in the prompt component. Ongoing medium-*z* SN surveys will yield more accurate parameters for our model.

Subject headings: galaxies: evolution — supernovae: general

Online material: color figures

1. INTRODUCTION

Type Ia supernovae (SNe Ia) play a pivotal role in astrophysics. On cosmological scales they serve as unparalleled distance indicators, providing direct evidence that the low-redshift universe is accelerating (Riess et al. 1998; Perlmutter et al. 1999). On galactic scales, they act as the primary source of iron, producing ≈0.7 $M_\odot$ per event (Tsujimoto et al. 1995), roughly an order of magnitude more than in core-collapse SNe (Hamuy 2005). On stellar scales, they represent an excellent example of explosive nuclear burning, resulting in radioactively powered light curves (see, e.g., Nomoto et al. 1984; Woosley 1990).

Nevertheless, many mysteries remain. While the peak magnitude and the decay time of SN Ia light curves are tightly correlated (Pskovskii 1977; Phillips 1993; Hamuy et al. 1995), the origin of this relation is poorly understood (see discussion in Pinto & Eastman 2000; Mazzali et al 2001). Similarly, while there is a consensus that SNe Ia originate from thermonuclear ignition and burning of a CO white dwarf in a binary system, it is uncertain whether they are triggered by accretion from a hydrogen-rich companion or from a merger with another white dwarf (see Branch et al. 1995). This uncertainty in the progenitor makes it difficult to predict the SN Ia rate in galaxies of varying masses, ages, and star formation rates.

Consequently, a wide range of models of this rate have been developed (e.g., Matteucci & Recchi 2001; Greggio 2005). These are commonly parameterized by a delay function, whose convolution with the star formation rate (SFR) yields the SN Ia rate. In principle, this is a completely general approach, as the SN Ia rate must depend on the mass and age of the underlying stars. In practice, most of this generality is lost to the assumption of a single "delay time" (e.g., Madau et al. 1998; Dahlén & Fransson 1999; Gal-Yam & Maoz 2004; Strolger et al. 2004). These fits are used to draw conclusions about SN Ia progenitors, the most recent example of which is the claim that there must be a 2–4 Gyr delay in all SNe Ia relative to the burst of star formation (Strolger et al. 2004).

However, this approach neglects the possibility that multiple evolutionary paths lead to SNe Ia. Indeed, there is direct observational evidence that this is the case. The brightest events (such as 1991T) only occur in actively star-forming galaxies, while substantially underluminous events (such as 1991bg) are most prevalent in E/S0 galaxies (Hamuy et al. 1996; Howell 2001; van den Bergh et al. 2005). This is an important clue that SNe Ia have at least two evolutionary channels with different characteristic times: one "prompt," basically tracking the current SFR, and another so delayed that it simply scales with the stellar mass (much as is seen in accreting binaries with low-mass companions, such as cataclysmic variables [Townsley & Bildsten 2005] or low-mass X-ray binaries in E/S0's [Gilfanov 2004]). We show here that in addition to explaining the SN Ia rates seen in nearby galaxies as described by Mannucci et al. (2005, hereafter M05), such a simple two-component model also resolves a wide range of outstanding issues.

We begin in § 2 by presenting the model, fitting the constants to observations of SNe Ia in nearby galaxies, and stating a few of the immediate repercussions. In § 3, we study the implications of this model in three important contexts: the iron content of galaxy clusters, the evolution of the average cosmic SN Ia rate density, and the [O/Fe] abundance ratios of Galactic stars. In § 4 we contrast this approach with other models, and we conclude in § 5.

2. THE TWO-COMPONENT MODEL

Following M05, we assume that there are two avenues for SNe Ia. Specifically, we adopt a model in which the SN Ia rate is the sum of two components: a term proportional to the total stellar mass, $M_\star(t)$ (regardless of its age) and a term proportional to the instantaneous SFR, $\dot{M}_\star(t)$,

$$\frac{\mathrm{SNR_{Ia}}(t)}{(100\ \mathrm{yr})^{-1}} = A\left[\frac{M_\star(t)}{10^{10}\ M_\odot}\right] + B\left[\frac{\dot{M}_\star(t)}{10^{10}\ M_\odot\ \mathrm{Gyr}^{-1}}\right], \quad (1)$$

where A and B are dimensionless constants that we fix with observations (see also eq. [2] of M05). The first of these terms is dominant in old stellar populations (and contains underluminous, 1991bg-like SNe), while the second term is most important in starbursts (and contains the brightest, 1991T-like SNe). To measure A, we use the recent observations from M05, who utilized detailed *K*-band data to update the analysis presented by Cappellaro et al. (1999). As there were 21 Type Ia SNe observed in E/S0 galaxies in this sample, and no instances of core-collapse supernovae, we consider the SFR term to be negligible in this population. This gives $A = 4.4^{+1.6}_{-1.4} \times 10^{-2}$.

M05 showed that the SN Ia rate was 0.35 ± 0.08 of the core-collapse rate in young stellar populations. Since they arise from massive, short-lived stars, the core-collapse SN rate should directly trace the SFR and thus can be used to determine B. Presently, the primary uncertainty in this measurement comes from relating the core-collapse rate to the SFR. We take two approaches to determining B, fully aware that ongoing SN surveys will soon reduce these uncertainties. First we use the $z \leq 1.0$ core-collapse SN rate density as measured by Dahlén et al. (2004), comparing it against the SFR density as measured by Giavalisco et al. (2004), and considering only the statistical error bars. This gives $\mathrm{SNR_{cc}}/\dot{M}_\star = (7.5 \pm 2.5) \times 10^{-3}\ M_\odot^{-1}$ and corresponds to a B-value for SNe Ia of 2.6 ± 1.1, which we adopt throughout this Letter.

An alternative approach is to use the blue ($B-K \leq 2.6$) population observed by M05, in which the measured SN Ia rate is $0.86^{+0.45}_{-0.35}$ per 100 yr per $10^{10}\ M_\odot$ of stars. The colors of these starbursting galaxies are consistent with a 0.7 Gyr population (M05), as computed from the population synthesis models of Bruzual & Charlot (2003). Within the errors, this gives $B = 1.2^{+0.7}_{-0.6}$, consistent with our first estimate.

Our values of A and B directly yield the relative contributions of these two components. For example, 10 Gyr after a starburst, only 20% of all SNe Ia will have come from the extended piece. Hence, in our model, most of the SNe Ia over any galaxy's lifetime come from the prompt contribution, as originally suggested by Oemler & Tinsley (1979).

Our model also allows for a comparison between SN types, as illustrated in Figure 1. In our model, by construction, the rate of core-collapse SNe is approximately 3 times the SN Ia rate in starbursting galaxies, while only SNe Ia are found in galaxies without star formation. For a galaxy with a total stellar mass of $10^{10}\ M_\odot$, the transition between these two regimes occurs at $\dot{M}_\star \approx 0.1\ M_\odot\ \mathrm{yr}^{-1}$, which corresponds to a Scalo parameter $b \equiv \dot{M}_\star(t)/\langle \dot{M}_\star(t)\rangle = \dot{M}_\star(t) t/M_\star(t) \approx 0.08$, or an age of 7 Gyr if we assume a star formation rate proportional to $e^{-t/(2\ \mathrm{Gyr})}$ as in M05.

Finally, since 0.74 $M_\odot$ of Fe is expelled in a typical SN Ia (Tsujimoto et al. 1995), while 0.062 $M_\odot$ is expelled in a typical core-collapse SN (Hamuy 2005), in any given starburst the overall SN Ia contribution to Fe production as compared with core-collapse SNe in our model is approximately 3 to 1.

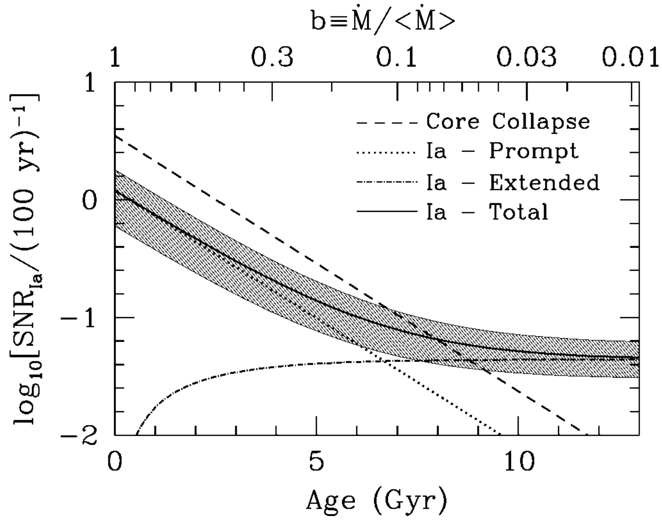

FIG. 1.—Supernova rate in a galaxy with a final stellar mass of $10^{10}\ M_\odot$. The solid line gives our model predictions for the SN Ia rate (bracketed by 1 σ errors), which is made up of the prompt (*dotted line*) and extended (*dot-dashed line*) components. The dashed line gives the core-collapse SN rate. In all cases we assume a star formation rate proportional to $e^{-t/(2\ \mathrm{Gyr})}$. Choosing a different characteristic star formation decay time would rescale the time axis while leaving the Scalo b-values unchanged. [*See the electronic edition of the Journal for a color version of this figure.*]

3. IMPLICATIONS AND PREDICTIONS

We now apply this model to three important issues. In this section and below, we adopt a Hubble constant of 70 km s^{-1} Mpc^{-1} and total matter and vacuum energy densities of $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$ in units of the critical density (see, e.g., Spergel et al. 2003). First we consider the intracluster medium (ICM) in galaxy clusters, which is measured to have an Fe content $\approx 0.3\ Z_\odot$ (Baumgartner et al. 2005). Although clusters are dominated by elliptical galaxies, models that combine the observed SN Ia rate in elliptical galaxies with the total cluster stellar mass result in Fe estimates that are roughly an order of magnitude too small (e.g., Renzini et al. 1993; Renzini 2004). While Maoz & Gal-Yam (2004) were able to provide a single-component resolution to this problem, they were not able to reconcile this fit with SN Ia measurements in field galaxies. In fact, even ICM models that appeal to Fe production by pair-instability SNe from very massive primordial stars (e.g., Loewenstein 2001) fall far short of the observed metallicity (Scannapieco et al. 2003).

Our two-component model, however, addresses this issue from a different perspective. The dominant source of Fe is not the late-time SN Ia contribution, as observed in elliptical galaxies, but rather the prompt contribution, which took place at high redshifts. In the top panel of Figure 2, we plot the ICM metallicity as a function of redshift, assuming a star formation redshift of 3 and an ICM-to-stellar mass ratio of $M_{\mathrm{ICM}}/M_\star = 10 \pm 3$, as appropriate for 7 keV clusters (Lin et al. 2003). Again, we take the core-collapse SN rate to directly trace the SFR. This results in [Fe/H] values broadly consistent with observations and an order of magnitude higher than previous estimates (Renzini 2004). Our model also naturally predicts the recently observed lack of [Fe/H] evolution with redshift (Tozzi et al. 2003), a feature that does not appear in models dominated by late-time SNe Ia.

Next we turn to the cosmic SN Ia rate density, or the number of Type Ia SNe per year per comoving Mpc^3. We adopt a cosmic star formation rate density of $\log\,[\mathrm{SFR}/(1\ M_\odot\ \mathrm{yr}^{-1}\ \mathrm{Mpc}^{-3})] = -2.2 + 3.9\log(1+z) - 3.0\,[\log(1+z)]^2$, which is a simple fit to the most recent measurements (Giavalisco et al. 2004; Bouwens et al. 2004). The resulting SN Ia rate density is compared with observations in the bottom panel of Figure 2, providing an excellent match, except for the highest-redshift point from Dahlén et al. (2004). This is because at $z \approx 1$ our model is dominated by the prompt piece, and no corresponding dip is seen in the SFR density at this redshift. Furthermore, requiring agreement with this point is the source of the 2–4 Gyr delay time derived by Strolger et al. (2004). Thus a strong *prediction* of our model is that future observations will revise the $z \approx 1.5$ measurement upward. In fact, more detailed analyses of the SN Ia rate density at $z > 1$ represent the single best way to falsify (or confirm) our approach.

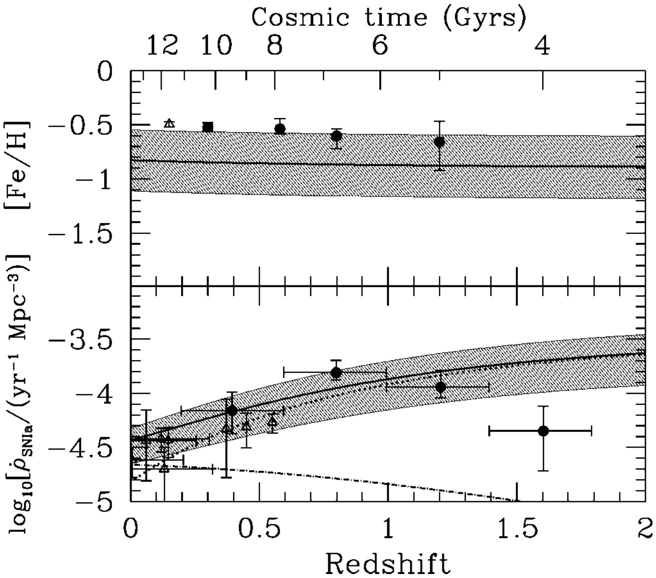

FIG. 2.—*Top*: [Fe/H] of the intracluster medium in $kT \geq 5$ keV galaxy clusters as a function of redshift. The solid line shows the results of our two-component model, with the 1 σ errors defining the shaded region. The low-redshift point (*open triangle*) is an average from the Baumgartner et al. (2005) sample, while the higher redshift points (*filled circles*) are from Tozzi et al. (2003). *Bottom*: Type Ia SNR density, as a function of redshift (*solid line*), which is the sum of the prompt (*dotted line*) and extended (*dot-dashed line*) components. Again the solid line corresponds to our two-component model, with the 1σ errors given by the shaded region. The lower redshift measurements (*open triangles*) are taken (in order of increasing redshift) from Cappellaro et al. (1999), Hardin et al. (2000), Blanc et al. (2004), Reiss (1999), Pain et al. (1996), Tonry et al. (2003), and Pain et al. (2002). The higher redshift measurements (*filled circles*) are from Dahlén et al. (2004). [*See the electronic edition of the Journal for a color version of this figure.*]

Finally we turn to the measured abundance ratios of Galactic stars, which probe the relationship between Type Ia and core-collapse SNe at short times. In particular, we compare iron with oxygen, an α-element that is synthesized primarily in core-collapse SNe. We take 0.14 $M_\odot$ of oxygen per SN Ia (Tsujimoto et al. 1995), 1.2 $M_\odot$ oxygen per core-collapse SN (a Salpeter initial mass function average computed in Scannapieco et al. 2003), and a closed-box model. Following M05, we adopt a star formation rate $\dot{M}_\star = M_{\rm gas} \exp[-t/(2\ {\rm Gyr})]/(2\ {\rm Gyr})$, which results in the [Fe/H] and [O/Fe] values shown in Figure 3.

As the overall SN Ia Fe contribution as compared with core-collapse SNe in our model is nearly 3 to 1, [O/Fe] should drop by a factor of 3, as observed. The value of [Fe/H] where this drop occurs, however, depends on the star formation model and requires a short delay in the prompt component. Assuming that both the core-collapse and the prompt Type Ia contributions exactly trace the SFR would fix the [O/Fe] values to a constant, in conflict with measurements of metal-poor halo stars. On the other hand, delaying the prompt component by 0.7 Gyr allows core-collapse SNe to briefly dominate the initial gas enrichment but has no impact on the SN Ia distribution on the timescales probed by other measurements. The timescale of this delay is proportional to the assumed SFR decay time, and a model with an SFR decay time of 1.0 Gyr and a prompt SN Ia delay of 0.35 Gyr would give equivalent [O/Fe] values. In any case, this delay is so short on cosmic times that we will continue to refer to this component as "prompt."

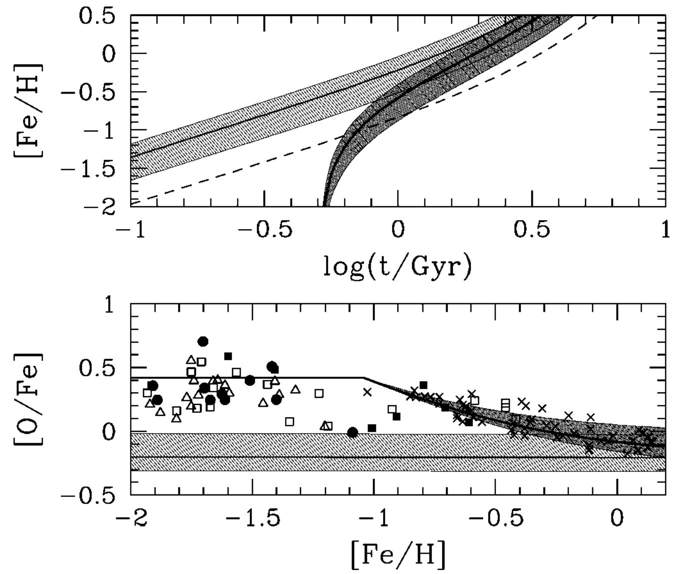

FIG. 3.—*Top*: Evolution of the Fe content in a closed-box system as a function of the age of the stellar population, assuming an SFR proportional to $e^{-t/(2\ {\rm Gyr})}$. Here the (thin) upper solid line corresponds to our fiducial two-component model (bracketed by the 1 σ errors), while the dashed line gives the iron provided by core-collapse SNe. Finally, the (thick) lower sold line is the result of our delayed two-component model. *Bottom*: Variation of the [O/Fe] abundance ratio as a function of metallicity, in a simple closed-box model. The (thin) lower line gives the results of our fiducial model, while the upper (thick) line corresponds to the two-component model with a 0.7 Gyr delay in the prompt component. The data points are taken from observations of Galactic disk and halo stars compiled by McWilliam (1997), following the symbol convention used in his Fig. 3.

4. COMPARISON WITH OTHER WORK

We now compare our approach with other single-component fits. In particular, we consider three possible SN Ia delay functions: an exponential model in which $\Phi(\Delta t) = C \exp(-\Delta t/\tau)/\tau$ (Tutukov & Yungelson 1994; Madau et al. 1998; Gal-Yam & Maoz 2004), and two Gaussian models in which $\Phi(\Delta t) = C \times (2\pi\sigma^2)^{-1/2} \exp[(\Delta t - \tau)^2/(2\sigma^2)]$ and σ is either "narrow" ($\sigma = 0.2\tau$) or "wide" ($\sigma = 0.5\tau$) (Dahlén & Fransson 1999; Strolger et al. 2004). Each of these functions has two free parameters: a delay time τ and a normalization C, which we fit to the number of SNe Ia in the youngest ($B-K < 2.6$) and most evolved ($B-K > 4.1$) galaxies measured by M05. As in that study, we model both galaxy types with $\dot{M}_\star \propto \exp[-t/(2\ {\rm Gyr})]$ with an age of 0.75 ± 0.25 Gyr in the $B-K < 2.6$ population and 10.5 ± 1.5 Gyr in the $B-K > 4.1$ population, as is consistent with their observed colors and core-collapse SN rates. Note that these SFRs are averages over entire populations, rather than histories of individual galaxies. Within the 1 σ errors, we find τ-values of 0.5–1.6, 0.6–1.0, and 0.5–1.3 Gyr for the exponential, narrow Gaussian, and wide Gaussian models, respectively.

Applying these fits to the full range of galaxy populations measured by M05 indicates that the proper number of SNe Ia in old galaxies and starbursting galaxies is obtained only at the expense of a large number of SNe Ia in galaxies of intermediate age. For example, in a t = 5 Gyr population all three models predict ≥2 SNe Ia per 100 yr per $10^{10}\ M_\odot$, while the measured value is $0.19^{+0.08}_{-0.07}$ (M05). Furthermore, the ratio of Type Ia to core-collapse SNe at 5 Gyr is ≥4, while the measured ratios are $\leq\frac{1}{3}$. On the other hand, our two-component model, shown as the solid line in Figure 1, falls within the range of observed values at all ages.

5. CONCLUSIONS

Our two-component model is motivated by the observed dichotomy between the environments of the brightest (1991T-like) and the faintest (1991bg-like) SNe Ia. Yet in some sense it is simply an application of the delay function formalism, in which the SN Ia rate is described as a convolution of an unknown function with the overall star formation history. Other models were limited by the assumption of a single "delay time" and had difficulties in reconciling the Fe content in clusters with the ratio of core-collapse to Type Ia SNe as a function of galaxy age (e.g., Maoz & Gal-Yam 2004). Our model solves this problem because it is dominated by a prompt component but allows significant numbers of SNe Ia to occur at late times. In addition, it produces the observed cosmic SN Ia rate to $z \leq 1$, while also fitting observations of E/S0's. The strongest test of this model is the measurement of the SN Ia rate at $z > 1$, which we predict to be in the range (1–3.5) $\times 10^{-4}$ yr^{-1} Mpc^{-3} at $z = 2$.

Of course, star formation does occur in some elliptical galaxies, and as shown in Figure 1, our simple model predicts that prompt SNe Ia will be the dominant component in such objects if $\dot{M}_\star/\langle \dot{M}_\star \rangle \gtrsim 0.1$. An example of such a case is the slow-declining Type Ia SN 1998es, which occurred in the early-type galaxy NGC 632. While this galaxy is fairly red ($B-K > 3$), spectral observations uncover significant star formation (Gallagher et al. 2005). Conversely, underluminous SNe Ia should occasionally be found in star-forming galaxies, such as the rapidly declining SN 1999by. While the host galaxy of this SN Ia is an Sb galaxy, imaging shows that it took place in the old population of halo stars (Gallagher et al. 2005).

SNe Ia play a pivotal role in astrophysics, and thus our two-component model has many implications. It allows for an updated assessment of Clayton & Silk's (1969) hypothesis that the γ-rays from radioactive decays explain the extragalactic MeV background (see Watanabe et al. 1999; Ruiz-Lapuente et al. 2001; Ahn et al. 2005). It highlights the usefulness of measurements that constrain Type Ia evolution at short timescales, such as studies of the distribution of SNe Ia relative to spiral arms (Maza & van den Bergh 1976; Bartunov et al. 1994; McMillan & Ciardullo 1996; Petrosian et al. 2005) and the Fe content of high-redshift quasars (Barth et al. 2003; Dietrich et al. 2003). It stresses the importance of early SNe Ia in ICM enrichment and exposes the limitations of one-component fits.

More generally, our model implies that over a Hubble time, ≈80% of the SNe Ia from any galaxy will occur within a Gyr of the initial starburst. The remaining 20% occur in a delayed fashion, clearly extending to times $\gtrsim$10 Gyr. This alludes to multiple progenitor scenarios: one that occurs "promptly," within a Gyr, and another that can occur a Hubble time after star formation. Perhaps this is not surprising given the openly debated range of possibilities (e.g., Branch et al. 1995; Greggio 2005) and the evidence for dominance (or absence) of some extreme SNe Ia in certain galaxy types. Deeper physical insights into how the age or metallicity of the accreting white dwarf might naturally cause this large range of diversity awaits theoretical work.

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