THE PROGENITORS OF TYPE Ia SUPERNOVAE

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ABSTRACT

Type Ia supernovae (SNe Ia) occur in both old, passive galaxies and active, star-forming galaxies. This fact, coupled with the strong dependence of SN Ia rate on star formation rate, suggests that SNe Ia form from stars with a wide range of ages. Here we show that the rate of SN Ia explosions is about 1% of the stellar death rate, independent of star formation history. The dependence of SN Ia rate on star formation rate implies a delay time distribution proportional to $t^{-0.5\pm0.2}$. The single-degenerate channel for SNe Ia can be made to match the observed SN Ia rate–SFR relation, but only if white dwarfs are converted to SNe Ia with a uniform efficiency of about 1%, independent of mass. Since low-mass progenitors are expected to have lower conversion efficiencies than high-mass progenitors, we conclude that some other progenitor scenario must be invoked to explain some, or perhaps all, SNe Ia.

Subject headings: stars: evolution — supernovae: general
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1. INTRODUCTION

Type Ia supernovae (SNe Ia) are, next to gamma-ray bursts, among the most powerful transient objects in the universe. SNe Ia are widely believed to be explosions of C+O white dwarfs (WDs) whose mass has grown by accretion to the Chandrasekhar mass of $1.4 M_\odot$ (Chandrasekhar 1931). Evidence for this includes total energy released (consistent with conversion of C+O to Fe), lack of hydrogen in the maximum light spectra (consistent with an object whose envelope has been lost), light-curve shape (broadly in agreement with energy deposition from radioactive decay of Fe-peak elements, as expected for exploding C+O WDs), and the occurrence of SNe Ia in old ($\sim10$ Gyr) stellar populations containing only low-mass stars (for which exploding WDs represent the natural, and perhaps only possible, SN Ia progenitor).

Beyond this consensus on the exploding WD model, the precise nature of the progenitors of SNe Ia remains poorly constrained. Progenitor models are broadly classified as “single degenerate” (SD), in which a white dwarf grows in mass by accretion from an evolving binary companion (Whelan & Iben 1973), and “double degenerate” (DD), in which two white dwarfs merge (Iben & Tutukov 1984; Webbink 1984). A variety of evolutionary paths may lead to SD and DD events (e.g., Livio 2001; Yungelson 2005; Parthasarathy et al. 2007; Greggio 2005).

The fact that SNe Ia are observed in elliptical galaxies has led to the persistent and widespread presumption that SN Ia progenitors are old, low-mass stars. Yet over the years there have been several hints suggesting that the SN Ia rate is enhanced in star-forming galaxies (e.g., Oemler & Tinsley 1979; van den Bergh 1990; Della Valle & Livio 1994). Two recent papers (Mannucci et al. 2005; Sullivan et al. 2006) have marshaled evidence for a strong dependence of the SN Ia rate on star formation rate (SFR), thus linking SNe Ia with young, massive stellar populations. Mannucci et al. (2005) made use of a sample of low-redshift supernovae discovered in five targeted searches (Cappellaro et al. 1999) and demonstrated a strong dependence of specific SN Ia rate (rate per unit mass) on morphology or galaxy color. This result was confirmed and extended by Sullivan et al. (2006), who analyzed a sample of spectroscopically confirmed SNe Ia (redshift $z = 0.2–0.75$, spanning cosmic time $7–11$ Gyr after the big bang) from the Supernova Legacy Survey (SNLS; Astier et al. 2006).

The SN Ia rate–SFR correlation found by Sullivan et al. (2006) is shown in the lower panels of Figure 1 (both axes are normalized by galaxy mass). Passive galaxies are plotted as a single data point in the lower left-hand panel; most of these galaxies are old. The variation of SN Ia rate from passive galaxies to the most active galaxies is dramatic: passive galaxies possess a mass-normalized SN Ia rate that is a factor of 10 or more lower than found for active starbursting systems.

In this Letter we present a simple model for the SN Ia rate–SFR relation in terms of stellar evolutionary timescales. This model, which is based on the SD scenario, allows an estimation of the efficiency of conversion of white dwarfs into SNe Ia. This provides, as we shall see, a constraint on the nature of SN Ia progenitors.

2. THE MODEL

2.1. White Dwarf Formation Rates

A first step toward understanding the rate of SNe Ia in galaxies is a calculation of the rate at which WDs are formed in different stellar populations. It is well known that WDs ($M < 1.4 M_\odot$) form as the endpoint of stellar evolution for stars with initial masses $M < 8 M_\odot$ (e.g., Weidemann 2000; Kalirai et al. 2008 and references therein). The rate at which white dwarfs form clearly depends on evolutionary timescales as a function of initial stellar mass and the initial mass function, or IMF. For a Salpeter (1955) mass function $dn/dm \propto m^{-2.35}$ and a power-law approximation to evolutionary timescales $t_{\text{evol}} \approx 10^{10}(M/M_\odot)^b$ yr ($b = -2.5$), it can be shown that white dwarfs form from a pure instantaneous burst of star formation at a rate that decreases with time roughly as $t^{-(a+b+1)/b} \sim t^{1/2}$. This (somewhat counterintuitive) result is due to the fact that the evolutionary timescales of massive stars are so much shorter than...
for low-mass stars, even in the presence of a steeply sloped IMF favoring low-mass stars.

The results of a detailed calculation of WD formation rate are shown in the upper panels of Figure 1, using more exact evolutionary timescales (Buzzoni 2002) and a power-law SFR $\propto t^{-p}$ (e.g., Buzzoni 2005). [Other SFR(t) functions give equivalent results, as will be shown.] For passive systems (left-hand panels), we plot the WD formation rate per unit galaxy mass (WDR/M) for a starburst with age 7.9 Gyr (the approximate age of the universe at the mean redshift of the SNLS SNe). The shaded region in Figure 1 includes systems as young as 5 Gyr (which would have formed $\geq 2$ Gyr after the big bang for the most distant objects in the SNLS). For active systems with star formation, we plot WDR/M as a function of star formation rate per unit galaxy mass (SFR/M).

Remarkably, the form of this diagram is very insensitive to the details of star formation history (other than age). Old starburst models with increasing SFR(t) ($p < 0$) overlap young models with decreasing SFR ($p > 0$), and all of these models lie within the upper shaded region of the figure. A variety of composite stellar populations, comprising an old passive bulge/halo and a star-forming disk (with the proportion of bulge-to-disk mass given by Buzzoni 2005 to match observed galaxy colors), can be seen to fall in the shaded region of Figure 1, as do models with bursts of star formation. Models with exponentially decreasing SFR(t) match the locus of the SFR $\propto t^{-p}$ models, as do models constructed using the PEGASE.2 evolutionary infall scenario (Le Borgne & Rocca-Volmerange 2002). Finally, we note that the range of $B-K$ colors exhibited by all of these models spans the full dynamic range of color exhibited by real galaxies. We conclude that the locus of the white dwarf formation rate shown in Figure 1 is well determined, independent of uncertainties in the evolutionary models.

SFR/M has units of $T^{-1}$ and is approximately the inverse of the gas consumption timescale of a galaxy (if SFR were held constant). Identifying $\tau = (SFR/M)^{-1}$ as a characteristic mean age of a model, one expects $(WDR/M) \propto \tau^{-1/2} = (SFR/M)^{0.5}$, roughly as observed in Figure 1. The increase of WD formation rate with SFR/M is therefore a reflection of the fact that the mean age of stellar populations with a large SFR/M (small gas consumption timescale) is smaller.

2.2. Type Ia Supernova Rates and the Conversion Efficiency

These calculations of specific white dwarf formation rate, WDR/M, can now be compared with estimates of the SNe Ia rate per unit stellar mass as derived from the SNLS (Sullivan et al. 2006). Scaling the white dwarf formation rate curve by a factor $\eta_{obs} = 0.008$ provides an excellent match to the SNLS observations (and also to the observations of Mannucci et al. 2005).

However, to convert $\eta_{obs}$ (the ratio of SN Ia to WD formation rates) to the physically more interesting conversion efficiency $\eta$ (the fraction of white dwarfs that explode as SNe Ia), it is necessary to correct for the time delay, $\Delta t_{WD-SN}$, between the formation of a WD primary and an SN Ia event. In the case of an SD system, this delay is due to the residual time that it takes the secondary star (of mass $M_2 = q M_1$, where $q$ is mass ratio) to evolve. The available evidence suggests that the distribution of q is flat (Larson 2001), or even strongly peaked toward equal masses (Pinsonneault & Stanek 2006), for close binaries.

We have computed detailed models for SD binaries with different distributions of q, using both numerical integration and Monte Carlo techniques. A flat distribution in q results in rates that are $< 2$ times lower than for “undelayed” q = 1 models (see Fig. 2). Most important, this factor is nearly constant for all SFR/M. Correcting $\eta_{obs}$ for the distribution of q-values yields a white dwarf to SN Ia conversion efficiency $\eta$ in the range $0.01$–$0.015$. [A power-law distribution of mass ratios $N(q) \propto q^{4}$, corresponding to a distribution of secondary masses $N(M_2) \propto M_2^4$, results in constant $\eta$ provided that $x > -1.5$. A distribution of secondary masses drawn from the IMF gives WDR/M $\propto$ constant, independent of SFR/M. This is discussed further in § 3 and in Pritchet et al. (2008, hereafter Paper II.).]

A calculation for the DD model is beyond the scope of this Letter. However, we note that a similar result ($\eta = \text{constant}$) is obtained if the distribution of semimajor axes for DD binaries is independent of mass (Paper II). We also note that $\eta \approx 0.01$ is valid for any mass range dominated by the SD channel.

An alternative way of describing the data is through the delay time distribution (DTD). From § 2, it can be seen that the data are consistent with a DTD $\propto t^{-0.5}$ (for a burst). Figure 3 shows that the data are bracketed by DTD $\propto t^{-0.3}$ and $t^{-0.7}$.

In summary: the SNIa rate is approximately 1% of the stellar death rate, from passive galaxies (SFR = 0) to starburst galaxies (SFR/M $\geq 10^{-9}$ yr$^{-1}$), with little dependence on the details of the stellar population mix. The dependence of SN Ia rate on star formation rate in both active and passive galaxies is independent of mass (Paper II).

\footnote{Note that $\eta$ includes the binary fraction—e.g., if the fraction of binaries were 0.5, then the fraction of WDs in binaries that become SNe Ia would be $\sim 0.02$. Available evidence (Lada 2006) suggests that the fraction of binaries increases with mass.}
is consistent with a simple timescale model based on the SD scenario, with a uniform WD conversion efficiency \( \eta \approx 1\% \) for all stars. The SN Ia rate–SFR rate dependence is also consistent with a continuous DTD \( \propto t^{-0.3} \). If more than one channel produces SNe Ia, \( \eta \approx 1\% \) still holds for any progenitor mass range in which the SD channel is dominant.

Our models are different from those of Greggio (2005) since we consider the scaling of the SN Ia rate with SFR, thus minimizing the effects of variations in star formation history. In addition, our models do not initially include variations of \( \eta \) with mass (for reasons that will become apparent). However, the slope of the DTD for a simple aging burst agrees with that of Greggio (2005, Fig. 3) for \( t < 1 \) Gyr.

2.3. Uncertainties in the Conversion Efficiency

What is the uncertainty in the efficiency factor \( \eta \)? Changing the functional form of SFR(\( t \)) has already been eliminated as a source of error. Changing the IMF to a two-piece or three-piece IMF (Kroupa 2007) (with increasing power-law slope at higher mass) remains consistent with the locus of white dwarf models in Figure 1, provided \( \eta \) is reduced by 25\%. Systematic errors in mass affect the vertical placement of data points in Figure 1, and these could be a factor of 2 or larger. Systematic errors of a factor of 2 in SFR/M affect \( \eta \) by about 40\%. The overall completeness of the SNLS rates, from which \( \eta \) was derived, approaches 100\% (Sullivan et al. 2006). It thus appears that the efficiency factor \( \eta \) is accurate to about a factor of 2. Most important, the relative efficiency factor between galaxies of different SFR/M should be unaffected by these systematic errors.

2.4. Comparison with Other Values of Conversion Efficiencies

Is \( \eta = 0.01 \) reasonable from other considerations? This is a difficult question to answer. Theoretical models (e.g., Yungel-son 2005) give efficiencies in the range 0.001–0.01 but are subject to a host of uncertainties (e.g., the distributions of binary mass ratios and separations, and the precise evolutionary scenario for SNe Ia). For the Milky Way, the observed SN Ia rate (Cappellaro & Turatto 2001) and WD formation rate (cf. Phillips 2002; Soker 2006) yield \( \eta \approx 0.1\%–2\% \). This number is extremely uncertain, but it would seem to rule out conversion efficiencies larger than a few percent.

Other observational determinations of efficiency (from the ratio of SNe Ia to core-collapse SNe, from the A and B rate parameters (Scannapieco & Bildsten 2005) and from abundances) span a huge range (1\%–40\%), even approaching 100\% for intermediate-mass stars (Maoz 2008). Part of this discrepancy is due to the different progenitor mass range (3–8 \( M_\odot \)) used by Maoz; however, our determination of \( \eta = 0.01 \) will still apply for any mass range dominated by the SD channel. To raise the value of \( \eta \) to 0.1 would require 90\% SN Ia incompleteness in the SNLS or SFR values that are overestimated by a factor of 100. Both of these possibilities are untenable.

3. IMPLICATIONS FOR SN Ia PROGENITORS

We now turn to relative values of \( \eta \) for populations with different SFR. The relative WD to SN Ia conversion efficiency \( \eta \) can be measured directly in Figure 1 for populations with different SFR/M, i.e., mean age or mass. In particular, it can be seen that the conversion efficiency for old stars in passive galaxies is similar to that for the most active starburst galaxies. The variation of \( \eta \) with SFR is smaller than a factor of 2.

The SD model results in lower conversion efficiencies \( \eta \) for low-mass stars, for a variety of reasons. A passive 10 Gyr old population is populated with stars with \( M \leq 1 \ M_\odot \), and because of mass loss on the giant branch, such stars produce white dwarfs of mass 0.5 \( M_\odot \) (Weidemann 2000; Kalirai et al. 2008). A binary system initially comprising two 1 \( M_\odot \) stars would therefore not evolve into a 1.4 \( M_\odot \) white dwarf unless mass...
transfer were exceptionally efficient. Below about $2M_\odot$ (turn-off age 1 Gyr), a He (rather than C+O) white dwarf is the likely outcome in a close binary (Greggio 2005), and such stars do not produce SNe Ia. The evolutionary time of the secondary sets the clock for the SN Ia explosion, and at low mass, some fraction of the secondaries have not yet completed their evolution. An increasing binary fraction with mass (Lada 2006) lowers the SN Ia rate at low mass relative to high mass. All of these factors will conspire to produce lower efficiencies at low SFR/$M_*$, relative to the most active galaxies.

The models of Greggio (2005) represent SD efficiency at low mass by including a continuous variation of $\eta$ for $M_* < 2M_\odot$, with $\eta_{M_*/M_\odot} < 0.1$. The result of such an efficiency variation is shown in Figure 3. Normalizing the models to the most active galaxies, the computed and observed SN Ia rates for passive galaxies disagree by a factor of 7. If SD progenitor scenarios are less efficient at low mass, as is expected, then SD progenitors cannot be the only objects producing SNe Ia; some other class of model (perhaps the double-degenerate model) must be invoked to explain some, and perhaps all, SNe Ia. A similar conclusion has been reached by, for example, Greggio (2005) and Yungelson & Livio (2000). This conclusion is also consistent with the observational lack of hydrogen in the late-time ejecta of SNe Ia (Leonard 2007).

If secondary star masses for close binaries were drawn from the IMF, then close binaries with a high-mass primary and low-mass secondary would be common, and the number of SNe Ia in old progenitors would be enhanced, compensating for the expected lower conversion efficiency at $M < 2M_\odot$. We reiterate, however, that the available evidence supports an IMF for secondaries in close binaries that is not drawn from the field IMF (e.g., Larson 2001; Pinsonneault & Stanek 2006).

The most subluminous SNe Ia (strange parameter $s < 0.8$) are neglected in the rates (Sullivan et al. 2006). Including these objects (mostly in passive galaxies) makes the disagreement between observations and predictions of the SD scenario even more extreme. A strong type-dependent incompleteness (with 90% incompleteness for starburst galaxies) would be required to explain the observations; there is no evidence for such an extreme effect.

4. CONCLUSIONS

The SN Ia rate is about 1% of the white dwarf formation rate, for all star formation rates and for a wide range of stellar population mixes. The SN Ia rate is also consistent with a continuous delay time distribution $\sim 0.5 \pm 0.2$. The dependence of the SN Ia rate on SFR matches the predictions of a simple timescale model based on the single-degenerate channel, but only under the (unrealistic) assumption that the fraction (1%) of white dwarfs exploding as SNe Ia is independent of progenitor mass. We conclude, as have others (e.g., Greggio 2005; Yungelson & Livio 2000), that a class of model other than the SD model must be invoked to explain at least some SNe Ia. Nevertheless, the conversion efficiency of 1% holds for any mass range dominated by the SD channel. This conclusion is valid provided that secondary stars in close binaries have a distribution of mass ratios $q$ that is approximately flat or rising toward $q = 1$. Clearly there is a need for a better understanding of the distribution of secondary masses in close binaries.

Finally, it should be noted that the predictions of SN Ia rate in this Letter provide a better match to observations than does the empirical $A \times M + B \times SFR$ formula (Scannapieco & Bildsten 2005; Sullivan et al. 2006). The implications of this will be discussed in Paper II.

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