TYPE IA SUPERNOVAE: COLORS, RATES, AND PROGENITORS

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ABSTRACT

The rate of type Ia supernovae (SNe Ia) in a galaxy depends not only on stellar mass, but also on star formation history (SFH). Here we show that two simple observational quantities (g−r or u−r host galaxy color, and r-band luminosity), coupled with an assumed delay time distribution (DTD) (the rate of SNe Ia as a function of time for an instantaneous burst of star formation), are sufficient to accurately determine a galaxy’s SN Ia rate, with very little sensitivity to the precise details of the SFH. Using this result, we compare observed and predicted color distributions of SN Ia hosts for the MENeaCS cluster supernova survey, and for the SDSS Stripe 82 supernova survey. The observations are consistent with a continuous DTD, without any cutoff. For old progenitor systems, the power-law slope for the DTD is found to be $-1.50^{+0.19}_{-0.15}$. This result favors the double degenerate scenario for SN Ia, though other interpretations are possible. We find that the late-time slopes of the DTD are different at the 1σ level for low and high stretch supernova, which suggest a single degenerate (SD) scenario for the latter. However, due to ambiguity in the current models’ DTD predictions, SD progenitors can neither be confirmed as causing high stretch supernovae nor ruled out from contributing to the overall sample.

Key words: supernovae: general

1. INTRODUCTION

Hoyle & Fowler (1960) were the first to suggest that at least some supernovae originate in explosions of degenerate C + O white dwarfs (WDs); there is strong circumstantial (Pritchet et al. 2008; Bloom et al. 2012) and direct (Nugent et al. 2011; Bloom et al. 2012; Piro & Nakar 2013) evidence that this picture is substantially correct. We now know that roughly 1% of all WDs eventually end their lives as Type Ia supernovae (SNe Ia; Pritchet et al. 2008), and that these WDs are almost certainly members of binary or multiple star systems; yet the precise progenitor and mechanism that leads to an explosion remains elusive.

The importance of understanding SN Ia progenitors and explosion mechanisms cannot be overemphasized. Dark energy was discovered using observations of intermediate redshift ($z < 1$) SNe Ia (Riess et al. 1998; Perlmutter et al. 1999); more recent observations of larger samples of supernovae have been used to constrain the nature of dark energy (Sullivan et al. 2011). However, only with a better understanding of the supernova explosions themselves can we hope to understand the calibration of SNe Ia as distance indicators, and evaluate the effects of potential redshift-dependent systematics. Furthermore, SNe Ia are the primary source of Fe-peak elements; understanding the origin of SNe Ia is therefore a key to mapping the buildup of metals in the early universe (e.g., Thielemann et al. 1986; Tsujimoto et al. 1995).

Most of the discussion of the origin of SNe Ia centers on the single degenerate (SD) and double degenerate (DD) scenarios. In the SD scenario (Whelan & Iben 1973; Nomoto et al. 2000), an SN Ia occurs when a CO WD accretes enough material from an evolving binary companion to drive it close to the Chandrasekhar limit, $M_{\text{Ch}} \approx 1.4M_\odot$. (Chandrasekhar 1931). A merger of two WDs (the DD scenario) may also lead to an SN Ia progenitor if the combined mass exceeds $M_{\text{Ch}}$. (Tutukov & Yungelson 1981; Webbink 1984). In addition, there exist sub-Chandrasekhar mass models (involving double detonations; e.g., Shen et al. 2010) and core degenerate models (involving the merger of a WD with the core of an AGB star; e.g., Soker et al. 2013). van Kerkwijk et al. (2010) propose that the DD channel can trigger SNe Ia even if the combined mass of the WDs does not exceed $M_{\text{Ch}}$. Many problems exist in the explosion physics and theoretical rates for these and other scenarios (Wang & Han 2012; Hillebrandt et al. 2013).

SNe Ia were originally assumed to belong exclusively to old stellar populations, due to their occurrence in elliptical galaxies. Branch & van den Bergh (1993) were among the first to show that SNe Ia also occur in young stellar populations; it is now known that SNe Ia are a factor ~10−30 more frequent (per unit mass) in young starburst galaxies than in old galaxies (Sullivan et al. 2006; Smith et al. 2012). This is not a surprising result, given that, through mass loss, stars as massive as ~5.5 $M_\odot$ (main sequence (MS) lifetimes ~100 Myr) can end their lives as CO WDs (Chen et al. 2014). (Stars with initial masses 5.5 $\lesssim M/M_\odot \lesssim 8$ end their lives as O+Ne WDs, which probably do not explode (Chen et al. 2014, though see Marquardt et al. 2015). Stars more massive than ~8 $M_\odot$ end their lives as either black holes or neutron stars after a core collapse supernova (Heger et al. 2003).)

What is known about the rates of SNe Ia? The SN Ia delay time distribution (DTD) gives the rate of SNe Ia from an instantaneous burst of star formation as a function of time, normalized to the burst mass. (The stellar mass of a burst decreases with time due to evolution and mass loss. By convention the DTD is normalized to the initial mass formed in a burst of stars.) The DTD depends on, and provides insight into, the progenitor channel. Unfortunately, binary population synthesis models (e.g., Maoz et al. 2014 and references therein) give widely disparate estimates of the DTD (as much as a factor of 103 different in some cases), and underestimate the overall rates by as much as a factor of ~10 (e.g., Wang & Han 2012).
The observational situation is somewhat more encouraging: the DTD has been found to vary roughly as $t^{-1}$ (Totani et al. 2008; Maoz et al. 2010; Graur et al. 2011; Maoz et al. 2012; Maoz & Mannucci 2012; Sand et al. 2012; Graur & Maoz 2013; Graur et al. 2014; Rodney et al. 2014), a functional form that is appealing because it agrees with simple gravitational energy loss timescales for merging WDs (Maoz et al. 2014). But determining the DTD relies on measuring the ages of individual galaxies, and these ages are notoriously inaccurate, especially in the presence of complex star formation histories. Even more troublesome is the fact that SN progenitors are drawn with non-uniform probability from the age mix of stars in a galaxy; in other words the mean stellar age may not necessarily be the mean age of SN Ia progenitors. As a simple toy model, consider an old galaxy with a very weak burst of recent star formation (RSF), and a DTD with a cutoff at late times (i.e., an upper limit on the age of progenitors). SNe Ia will occur in the young stars in this galaxy, but these supernovae may be (erroneously) attributed to the dominant old population. In more detail, if DTD $\propto t^{-1}$, it follows that the rate of SNe Ia per unit mass can vary by a factor of 100 depending on the age of a star burst (which can vary from roughly $10^8$ to $10^{10}$ years). A 1% (by mass) burst of star formation can in principle provide an SNe Ia rate equivalent to that of the (much more massive) old population of a galaxy. Is it therefore possible that SNe Ia in old elliptical galaxies originate only in a “frosting” of young stars, and that all SNe Ia belong to a relatively young ($\lesssim 10^9$ years) old stellar population? Put a different way, is there a cutoff in the SN Ia DTD?

There is in fact a physical basis for a DTD cutoff at late times. Primary stars with a mass less than $2 \, M_{\odot}$ (lifetime $\geq 10^9$ years) are more likely to produce an He WD than a CO WD (Yungelson 2005); if accretion then pushes such a star above $M_{\text{ch}}$, it will undergo an He flash rather than an SN Ia explosion (Greggio 2005). Even if a CO WD is produced, an accretion rate around $10^{-7} \, M_{\odot} \, \text{yr}^{-1}$ is required for stable burning and mass growth (Nomoto 1982, and this will only occur if the secondary also has a mass $\geq 2 \, M_{\odot}$ (Han & Podsiadlowski 2004; Maoz et al. 2014). Thus a cutoff $t_c$ in the DTD around $10^9$ years might be expected for the SD scenario. (On the other hand, the discovery of high mass-ratio binaries among massive stars (Moe & Di Stefano 2015) indicates the presence of low mass MS companions, potentially allowing longer delay times for the SD scenario. This, however, is only relevant if the $M > 2 \, M_{\odot}$ constraint for the secondary is relaxed.)

The observational evidence for or against a break in the DTD is ambiguous. Some (but not all) of the data in the compilation of Maoz et al. (2014) hints at a break (e.g., Maoz et al. 2011, 2012), but with large uncertainties. Schawinski (2009) uses GALEX NUV – r color to show that SNe Ia observed in early-type galaxies might be due to episodes of RSF, and hence that the DTD may have a cutoff.

In this paper, we study the nature of the DTD and whether it has a break or cutoff, using existing samples of SNe Ia. We use a simple stellar population (SSPs) model to calculate supernova rates as a function of galaxy color, for a variety of DTDs. We then predict the color distribution of SN hosts using a control sample of galaxies, which consists of galaxies from which the SN hosts were drawn. Following this, we compare this color distribution with that observed for actual SN hosts. In particular, we search for a deficit of SNe Ia at the color of the red sequence (RS) relative to predicted rates. If observed, such a deficit could be interpreted as due to the effects of a cutoff in the DTD.

Section 2 discusses the supernova surveys and control samples that were used; Sections 3–5 explain the stellar population models and the methodology. Sections 6 discusses the results. We use cosmological parameters from the Planck collaboration (Ade et al. 2014): $H_0 = 67 \, \text{[km s}^{-1} \text{Mpc}^{-1}]$, $\Omega_\Lambda = 0.68$, and $\Omega_m = 0.32$.

2. SAMPLE SELECTION

We analyze two low redshift samples of supernovae and field galaxies: the Multi-Epoch Nearby Cluster Survey (MENeaCS) in $g - r$, and the Sloan Digital Sky Survey Stripe 82 (SDSS-II) in $g - r$ and $u - r$. We compute the cumulative supernova rate we would expect to observe in each survey. In order to do this, we define a control sample, which consists of galaxies that satisfy the selection criteria discussed below.

2.1. MENeaCS Supernova Survey

The MENeaCS survey (Sand et al. 2012) sampled 57 X-ray selected rich clusters with redshifts $0.05 < z < 0.15$. Repeated $g$- and $r$-band observations of these clusters were obtained over a 2 year period using the Canada–France–Hawaii Telescope with its MegaCam imager (Boulade et al. 2003). The detection limit was $g = r = 23.5$ in the difference imaging. MENeaCS spectroscopically confirmed 23 cluster SNe Ia, 4 of which were almost certainly intrachannel events which are not used in our analysis (Sand et al. 2011; Graham et al. 2015). Other than for SN Ia hosts, some clusters have spectroscopy available in archival sources (Sifón et al. 2015), including the SDSS, which we use to study environmental effects on our samples in Section 3.2. Additional $u$- and $r$-band photometry is also available (see van der Burg et al. 2015), which we do not use since our results with the SDSS data show that the $g - r$ color leads to smaller uncertainties.

The initial control sample contains 57,638 galaxies. For simplicity, we adopt a redshift $z = 0.1$ for all objects to compute the absolute magnitude in the $r$-band, $M_r$. In order to exclude objects with spurious photometry we require $-23.5 \leq M_r < -17.5$, which reduces the number of galaxies in the control sample to 56,523. Out of the 19 cluster hosts, 5 do not satisfy the color (see Section 5) and magnitude selection criteria we adopt for our control sample; we do not consider these hosts in our analysis. Our MENeaCS sample of SN Ia hosts therefore contains 14 galaxies.

2.2. SDSS-II Supernova Survey

The SDSS-II Supernova Survey (Frieman et al. 2008) covered a 300 deg$^2$ region of Stripe 82 ($-60^\circ < \alpha < 60^\circ$, $-1^\circ25 < \delta < 1^\circ25$) over nine months during 2005–2007 (with some engineering time in 2004). Of the more than 500 SNe Ia that were spectroscopically confirmed, we select those with hosts bright enough to have spectroscopy in the SDSS DR7 catalog$^5$ ($14 < r < 17.77$, after correction for Milky Way extinction). We follow the host-matching procedure of Sullivan et al. (2006), described in detail by Gao & Pritchet (2013).$^6$

$^5$ http://www.sdss.org/dr7/

$^6$ See Sand et al. (2011) for the correction of a typo in Sullivan et al. (2006).
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Table 1

| Color | Sample   | Slope | \( \sigma \) |
|-------|----------|-------|-------------|
| \((u - r)\) | MENeACS  | \ldots | \ldots     |
|       | SDSS     | \(-0.069\) | 0.21       |
| \((g - r)\) | MENeACS   | \(-0.026\) | 0.039      |
|       | SDSS     | \(-0.0188\) | 0.04       |

The final sample of SNe Ia is 53 in the redshift range \(0.01 < z < 0.2\). The control sample contains 20,707 galaxies.

The analysis of stellar populations in field galaxies and SN Ia host galaxies uses ugriz Petrosian magnitudes from the SDSS DR7 database, specifically \(u - r\) and \(g - r\) colors, which are the most sensitive to age and star formation effects (in the observed \(z\) range).

3. COLOR AND ABSOLUTE MAGNITUDE CALCULATION

Colors and absolute magnitudes are required for the analysis we perform in this work. These are calculated as follows.

3.1. Absolute Magnitudes

First, we correct the observed apparent magnitudes for galactic extinction using the Schlegel et al. (1998) extinction map. Absolute magnitude is then calculated using:

\[
M_X = m_X - 5 \log_{10}D_L - 25 - K_X(z) + Q \cdot z,
\]

where \(X\) is passband and \(D_L\) is luminosity distance. The \(k\)-correction to redshift zero, \(K_X(z)\), is calculated using KCORRECT (Blanton & Roweis 2007); the evolutionary correction, \(Q \cdot z\), is made using \(Q = 1.6\) (Wyder et al. 2007).

3.2. Red-sequence Fitting

The RS is, roughly speaking, the locus of the oldest galaxies in a color–magnitude diagram (Strateva et al. 2001; Wyder et al. 2007). The color of an RS galaxy is correlated with its absolute magnitude or mass; this dependence is known as the color–magnitude relation (CMR), where the reddest of the RS galaxies are the brightest and largest. The CMR (and scatter around it) is the product of a variety of effects, but particularly variations in metallicity and age (Graves et al. 2009).

For simplicity we measure all colors relative to the fitted RS:

\[
\Delta = \Delta(g - r) = (g - r) - (g - r)_{RS},
\]

and similarly for other passbands. This step removes some calibration errors, extinction errors, and also the slope of the CMR if \((g - r)_{RS}\) is measured at the same absolute magnitude as the galaxy in question. (As will be seen in Section 4.4, using color relative to the RS in the stellar population models has a similar beneficial effect.)

For MENeACS clusters, each cluster RS CMR was fitted; the CMR was subtracted from the data and the clusters co-added. This procedure eliminates field-to-field calibration and extinction differences.

Although the RS is generally associated with rich clusters, a strong RS is also present for (predominantly field) galaxies in SDSS Stripe 82. To fit the CMR of this sample, we first excluded objects that were clearly not part of the RS, and then used an iterative outlier rejection method. The RS slope, intercept and standard deviation are given in Table 1. In particular, the fitted slope of the SDSS \(g - r\) sample, \(-0.019\), is in agreement with the average value found for the MENeACS sample, \(-0.026\), and with the value obtained by Hogg et al. (2004), \(-0.022\), for field galaxies in different environments. Similarly, the linear coefficient of the \(u - r\) SDSS sample, \(-0.069\), is in agreement with the value found by Baldry et al. (2004) for SDSS field galaxies, \(-0.08\). The formal errors in these slopes are very small \((3 \times 10^{-4}\) for \(g - r\) and \(\sim 2 \times 10^{-3}\) for \(u - r\)), but the true uncertainties are dominated by systematic errors such as the age and metallicity dispersion in the RS.

Is the age and metallicity of the field RS in SDSS Stripe 82 the same as the cluster RS in the MENeACS data? To answer this question we examined regions of high density in Stripe 82 (which appear as “stripes” in the color-redshift diagram). No difference in RS color was observed between these regions and the entire sample. We also looked at \(\sim 25\) MENeACS clusters lying in the full SDSS DR7 footprint, comparing the colors of their RS with the surrounding field. The cluster RS was found to be 0.02 (0.06) mag redder in \(g - r\) and \(\sim 2 \times 10^{-3}\) for \(u - r\), but the true uncertainties are dominated by systematic errors such as the age and metallicity of the oldest populations does not affect our results.

4. STELLAR POPULATION MODELS

Galaxy colors were modeled using the Flexible Stellar Population Synthesis code (FSPS—Conroy et al. 2009, 2010; Conroy & Gunn 2010). We used the BaSeL spectral library (Lejeune et al. 1997, 1998; Westera et al. 2002), combined with PADOVA isochrones (Marigo & Girardi 2007; Marigo et al. 2008) and the Chabrier (2003) initial mass function (IMF). We assumed solar metallicity, and no shift in \(\log L\) and \(\log T\) for TP-AGB stars; the dust parameters, fraction of blue stragglers, and fraction of extended horizontal branch (EHB) stars were all set to zero. In Section 4.4 we address the consequences of varying the metallicity and EHB fraction adopted, finding no significant impact.

Initially we modeled the star formation history (SFH) of galaxies as a sum of two SSPs. This model has previously been employed to probe RSF in early-type galaxies (e.g., Ferreras et al. 1999; Ferreras & Silk 2000; Kaviraj et al. 2007; Schawinski et al. 2007). For this simple case there are three parameters that determine the properties of a galaxy: the ages of the young and old populations \(t_y\) and \(t_o\), and the mass fraction \(\alpha = M_y/M_o\) of the burst. (Here \(\alpha\) is defined in terms of the stellar mass initially formed in each component, and does not include the effects of later stellar evolution and mass loss.)

We also considered a wide range of more complicated star formation histories. Simplest of these are star formation rates that decay exponentially, \(SFR \propto \exp(-t/\tau)\) (e.g., Grazian et al. 2015). Other models involving gas infall, star formation, and winds (Le Borgne & Rocca-Volmerange 2002) were also used; for these models we tried a wide range of parameters that satisfy observed galaxy colors, with ages \(\leq 10\) Gyr. In all of these cases we also considered the effects of adding a burst (SSP) component with variable age and mass fraction \(\alpha\).
population. The solid curve labelled 1B is a SSP, i.e., young of a 10 Gyr SSP. The curves labeled 2B are double burst models. The color shift is relative to the RS, which in these plots is assumed to be the color of an SSP; as \( \Delta \) approaches zero, two-burst models converge to color difference curves that are independent of age, due to the effects of the He flash; however, this is significant only for large bursts (\( \alpha \gtrsim 0.3 \)), which are rare. In any case, the color and supernova rate predictions from these models are consistent with the predictions from more complex and realistic models, as we shall see.

4.1. Age–Color Relation

Using the FSPS predictions for a single SSP, we can calculate the color deviation from the RS, which is assumed to be the color of a 10 Gyr SSP. The color shift is relative to the RS. These plots are assumed to be the color of an SSP at \( t_0 = 10 \) Gyr.

Variations of a few Gyr in the age of the old population do not change our model predictions significantly because all colors are measured with respect to the RS. Figure 1 shows the predictions for color differences in \( u-r \) and \( g-r \) as a function of age, for a few simple SFHs. These curves present two prominent bumps, at \( \sim 10^7 \) years (due to the supergiant phase) and \( \sim 10^8 \) years (due to the helium flash). Larger mass fraction \( \alpha \) causes the two-burst model to approach the predictions of an SSP; as \( \alpha \to 0 \) the color difference curves approach zero. Two-burst models converge to color difference \( \Delta = 0 \) at \( t = t_0 \); on the other hand, the color shift of an exponentially declining SFH is not exactly zero at \( t = t_0 \), because \( \Delta \) is measured relative to an SSP.

4.2. Age–Supernova Rate Relation

The formation of CO WDs starts after \( t_{\text{WD}} \approx 100 \) Myr (Section 1), and so DTD (\( t < t_{\text{WD}} \)) \( \equiv 0 \). There is in fact excellent observational evidence that SNe Ia arise from stars older than \( \sim 100 \) Myr (Section 1), and also because the probability of observing a burst this young is very small (\( \sim 10^7 \) years/\( 10^9 \) years = \( 10^{-2} \)). There is also a possible degeneracy in the age–color relation at 1.1 Gyr, due to the effects of the He flash; however, this is significant only for large bursts (\( \alpha \gtrsim 0.3 \)), which are rare. In any case, the color and supernova rate predictions from these models are consistent with the predictions from more complex and realistic models, as we shall see.

In other words, age is not uniquely related to color difference.
We initially considered six cases: (i) a constant power slope $s_1 = s_2 = -0.5$; (ii) a soft break $s_1 = -0.5$, $s_2 = -1$; a constant power slope (iii) $s_1 = s_2 = -1$ and (iv) $s_1 = s_2 = -1.25$; (v) a break $s_1 = -1$, $s_2 = -2$; and (vi) a cutoff $s_1 = -1$, $s_2 = -3$. In all cases, we assume $t_{WD} = 10^8$ years and $t_c = 10^9$ years; as we shall see the results are not affected by the exact values of $t_{WD}$ and $t_c$. (We denote these six cases “$-0.5/-0.5$,” “$-0.5/-1$,” etc.) We also considered the effects of a drastic cutoff, $s_1 = -1$, $s_2 = -\infty$, where the SN rate drops to zero past $t_c$.

The DTDs (ii) and (iii) are derived from the DD channel; the slope $s_2 = -1$ for $t > t_c$ is set by energy loss from gravitational waves (Section 1). Case (i) assumes that the behavior of the DTD remains unaltered for $t < t_c$. In case (ii) we adopt the suggestion (van der Kerkwijk et al. 2010) that the DTD at $t_{WD} < t < t_c$ is dictated by the formation rate of WDs, $\propto t^{-0.5}$ (Pritchet et al. 2008). Cases (i) and (iv) represent a small deviation from the DD channel prediction. Cases (v) and (vi) assume a steeper slope beyond $t_c$, as predicted for the SD channel.

### 4.3. Color–Supernova Rate Relation

The specific SN Ia rate per unit mass, $sSNR_m$, is calculated from the convolution of the DTD with SFH. The predicted values are shown in Figure 2 for exponential models; age increases to the right for each curve. There is considerable dependence on SFH in these curves (a factor of $\geq 3$ at a given color for exponential SFHs, and more when other SFHs are considered), yet not much variation with DTD. It should be noted that these exponential models give good agreement with observed galaxy colors in both the $u - r$ versus $g - r$ diagram, and also the *GALEX NUV* $- r$ versus $g - r$ diagram (e.g., Wyder et al. 2007); these models match not only “red and dead” ellipticals (short timescale $\tau$), but also bluer galaxies (larger $\tau$), which populate the green valley and the blue cloud regions of the CMD.

For any SFH we can derive the mass-to-light ratio $M/L$ using the FSPS models. (Simple analytical expressions exist for the $M/L$ of the two-burst and exponential SFH cases.) We use $M/L$ measured in the $r$-band and adopt an absolute magnitude $M_{r,0} = +5$ to convert to solar units (though the exact value of $M_{r,0}$ does not affect the final analysis). Finally, we use $M/L_r$ to convert $sSNR_m$ to $sSNR_{L_r}$, the specific supernova rate per unit $r$-band solar luminosity.

Figures 3 and 4 show the relation between $\Delta$ and $sSNR_L$ for $g - r$ and $u - r$. Remarkably, the $\Delta$–$sSNR_L$ relation is only weakly sensitive to SFH, except for the steepest cutoffs in DTD. This conclusion also holds if we consider a wider range of SFHs (double bursts, more complicated SFHs involving infall, and combinations of all of these models with bursts), as can be seen in Figure 5. Finally, the same conclusion remains valid if luminosity is derived from the $g$ or $i$ bands (because the plots are in terms of color). By way of contrast, as we have already seen, the relation between $\Delta$ and $sSNR_m$ shows a great deal of SFH-dependent scatter.

The difference between $sSNR_m$ and $sSNR_{L_r}$ can be explained as follows. Consider an exponential burst of star formation, with SFR $\propto e^{-t/\tau}$. The spread in $sSNR_m$ at a given color (e.g., Figure 2) is due to the difference in mean age of the stellar populations; at fixed color, populations with longer $\tau$ are older, and hence have a lower $sSNR_m$. For $\tau = 1$ (10) Gyr, the mean age of stars in a stellar population that possesses $\Delta (g - r) = -0.4$ is 1.8 (5.8) Gyr. A $t^{-1}$ dependence of the DTD makes $sSNR_m$ for the $\tau = 10$ Gyr population a factor of $\sim 3$ lower than for the $\tau = 1$ Gyr population. But $M/L_r$ for $\tau = 10$ Gyr is a factor of 3 smaller, and so $sSNR_{L_r} = sSNR_m \times M/L$ is almost the same for the two populations. Thus the lack of dependence of $sSNR_{L_r}$ on SFH is due to a (somewhat fortuitous) cancellation of the effects of the DTD and the $M/L$. 

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**Figure 3.** SN rate per unit flux in the $r$-band as a function of color shift in $g - r$ (relative to the red sequence) for the same eight SFHs as in Figure 2. Each curve spans a range of ages, with $t = 10$ Gyr on the right (blue squares), which we use to construct the $\Delta (g - r)$–$sSNR_L$ relation. The scatter in the predicted rate is small, implying that the SN rate per unit flux is nearly independent of the SFH. We note that the colors of the exponential models match the colors of real galaxies. Each set of DTD curves has been vertically shifted for clarity.

**Figure 4.** Same as Figure 3 but for $u - r$. 

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**Figure 5.** The Astrophysical Journal, 834:15 (11pp), 2017 January 1
Another important point apparent in Figures 3–5 is that the shapes of the sSNR_L versus color curves are very sensitive to the DTD. Again, this is in contrast to the sSNR_m versus color curves.

The derived Δ−sSNR_L curves are powerful because they allow an accurate prediction of the SN Ia rate from two observed quantities (color and luminosity). Furthermore, these curves are robust in several ways: (i) as already pointed out, the curves in Figures 3–5 are insensitive to SFH. (ii) The rate predictions for distinct DTDs are quite different, implying that observations can be used to constrain the DTD. (iii) The results are not sensitive to various parameters that affect the stellar population models (Section 4.4). This is partly due to the fact that all colors are measured differentially relative to the RS.

4.4 Tests of the Stellar Population Models

To check the results from FSPS, we used PEGASE.2 (Fioc & Rocca-Volmerange 1997, 1999) models to produce age–color and age–luminosity relations for simple bursts. (PEGASE models use the older Padova evolutionary tracks coupled with the BaSeL (Lejeune et al. 1997, 1998) spectral library.) The results were indistinguishable from FSPS, even for the GALEX NUV bandpass (which we do not use in this paper).

We verified that our model is not strongly dependent on metallicity (0.006 < Z < 0.030) using two methods. First, we checked the dependence of the Δ versus sSNR_L relations on metallicity. While higher metallicities result in higher SN rates, the net effect of varying the metallicity is equivalent to a small vertical shift in sSNR_L at all Δ. Such a normalization change has no effect on our results.

In the second metallicity test we simulated the effects of the CMR on our results (assuming that the CMR is driven solely by metallicity). We allowed for a variation between Z = 0.030 for the brightest galaxies (M_r < −21.5) and Z = 0.005 for the faintest galaxies (M_r > −18.5). This has little effect on the predicted color distributions, for three reasons: (i) SN rates change by only ~26% between the high and low metallicity models; (ii) very few galaxies are present in the brightest and faintest bins, thus diminishing their relative weight; and (iii) perhaps most importantly, the effects of metallicity differences are mostly removed by measuring colors differentially with respect to the RS.

We also verified that our model is not strongly dependent on the age of the old population (6 < t_c, < 12 Gyr), the fraction of stars in the EHB (0.0 < EHB < 0.5), or the IMF adopted. (The EHB tests assumed a fixed EHB fraction in all galaxies. We will discuss the effects of varying the age of the cutoff in the DTD, t_c, in Section 6.) For the representative scenario of a two-burst with α = 0.01 and −1/−1 DTD, the net effect of changing each parameter, while keeping others invariant, can be very well approximated by an offset in the (nearly constant) sSNR_L.

We have assumed that the age of the youngest SN Ia progenitors is 100 Myr, and that WDs in the age range 40–100 Myr do not explode (Section 1). If, on the other hand, WDs in this age/mass range can explode as SNe Ia, the late time slope of the most likely DTDs quoted in Section 6 become shallower by < 0.1.

5. COMPARISON OF MODELS WITH OBSERVATIONS

The goal of this paper is to use the colors of galaxies to predict supernova rates for different stellar population mixes and DTDs. These rates can be directly compared with observations to test the validity of various DTDs, and in principle discriminate among different SN Ia progenitors.

The predicted host color distribution of supernovae is calculated as follows. For each galaxy in the control sample, we convert its color (relative to the RS), Δ, to an SN Ia rate per r-band solar luminosity, sSNR_L(Δ), via the relations presented in Section 4.3. We then calculate an absolute SN Ia rate, R(Δ), by multiplying the sSNR_L by the luminosity, R(Δ) = sSNR_L(Δ) · f_i. The flux f_i is computed using absolute k-corrected r magnitudes, so that it is consistent with the fluxes used to derive the M/L relations.

Generally, the scatter in the models grows as one moves to bluer colors. We therefore impose a color cut Δ (g − r) > −0.4, and Δ(u − r) > −1 for the SN hosts and control sample; these colors correspond roughly to the color of an SSP at age 10^9 years. While this indicates that our model is more sensitive to the slope of the DTD for t > t_c, our SFHs also probe earlier ages, as shown in Figure 1. We have verified that the exact value of this cut, which includes part of the blue cloud, does not affect the results. The red limit is set to be +2σ, where σ is the standard deviation of the RS CMR. The accepted Δ(g − r) ranges of the SDSS and MENeaCS samples are similar, because the measured σ’s are nearly the same (see Table 1). We assume sSNR_L(Δ ≥ Δ_max) = sSNR_L(Δ_max), where Δ_max is the color at 10 Gyr of the exponential SFH model with 1 Gyr timescale.
The models and observations are compared statistically using an approach developed by Maoz & Badenes (2010) (see also Gao & Pritchet 2013; Brandt et al. 2014). The probability of a galaxy hosting \( n \) supernovae is given by a Poisson distribution:

\[
L = \prod_i (\lambda_i)^{n_i} e^{-\lambda_i / n_i!},
\]

where \( \lambda_i \) is the normalized predicted rate and \( n_i \) is the number of SNe observed (0 or 1) in a given galaxy. Here

\[
\lambda_i = A \times R_i,
\]

where \( A = N_{\text{obs}} / \sum_i R_i \) is the normalization constant to predict the correct number of supernovae, and \( N_{\text{obs}} \) is the number of SNe observed in a given sample. It can be shown (e.g., Gao & Pritchet 2013) that the logarithm of the likelihood is simply:

\[
\ln L = -N_{\text{obs}} + \sum_j \ln \lambda_j,
\]

where \( j \) runs over galaxies that hosted an SN. We use Bayesian inference with uniform priors to calculate the most likely DTD for each sample.

For simplicity, we ignore the effects of marginalizing our rate predictions over the uncertainty in \( \Delta(\text{color}) \) and \( r \)-band magnitude. This is justified where the power-law slope is shallow, because the supernova rates are nearly constant (see Figures 3 and 4) and the \( r \)-band error is typically small (\( \pm 0.017 \)). On the other hand, steeper power-laws exhibit larger scatter around the \( \Delta-sSNR_\text{g} \) relation and therefore the uncertainty of these models is most likely dominated by systematic errors, which we do not take into account (a caveat of this work). The confidence levels are computed using the likelihood derived from Equation (5). Our results use a 68% confidence level, unless otherwise stated.

The overall normalization of the masses and rates has no effect on the shape of the DTD. Nevertheless, we note in passing that our model normalization (Section 4.2) overpredicts the total number of SNe Ia in the SDSS sample by a factor of \( \sim 2 \).

6. RESULTS

We present the supernova host color distributions for the MENeaCS cluster sample in \( g - r \) (Figure 6), and for the SDSS Stripe 82 SN Survey in \( g - r \) (Figure 7) and \( u - r \) (Figure 8). All results are shown as normalized cumulative rates as a function of \( \Delta(\text{color}) \), i.e., color relative to the RS, as computed in Section 3.2. Predictions from our simple model are also shown in these figures, for various DTDs. The predictions are smoothed with a Gaussian kernel whose standard deviation equals the \( \sigma \) of the RS. The supernova host observations are smoothed by the observational uncertainty in color. Finally, in Figure 9 we show the probability for various combinations of DTD slopes \( s_1 \) and \( s_2 \); from this probability calculation we compute a statistic to compare the observed and modeled color distributions for three cases: (i) a continuous power-law, \( s_1 = s_2 \); (ii) \( s_1 = -1.0 \) (the value expected theoretically for the DTD, and observed by several authors); and (iii) \( s_1 = -0.5 \) (corresponding to the formation rate of WDs). The results are given in Table 2.

A general conclusion is that a steep cutoff (\( -1/3 \) or steeper) cannot explain any of the observations. This drastic DTD is ruled out at the >99.99% level for all samples; there are simply too many supernovae in the oldest RS galaxies to allow such a sharp cutoff in the DTD (Figures 6–8). Nor is a color shift observed between the RS population as a whole and the colors of the oldest SN hosts; such a shift would have been expected if SNe Ia in RS galaxies were produced primarily by recent bursts of star...
formation. We therefore conclude that at least some SNe Ia must occur in old stellar populations. This result is complementary to those from Graham et al. (2012), who derived the rate of SN II in galaxy clusters from MENeaCS data, and used that measurement to evaluate the star formation rate in cluster ellipticals. They found that only a small fraction of cluster SNe Ia may originate from this “frosting” of young stars and experience a short delay time, and that cluster SN Ia rates remain an appropriate tool for deriving the late-time DTD.

Another general conclusion is that, if the DTD is continuous in power-law slope, then this power-law slope must not be steeper than $-1.8$ at 95% confidence level (all samples). The analysis of the SDSS in $g - r$ rules out continuous slopes as shallow as $-1$ at the same confidence level; such slopes are however permitted by the MENeaCS and SDSS $u - r$ samples.

### 6.1. MENeaCS

Figure 6 shows the cumulative observed rate and predictions. This sample is best described by a continuous power-law with $s_1 = s_2 = -1.26^{+0.57}_{-0.33}$, or by a broken power-law with $s_1 = -1$, $s_2 = -1.35^{+0.66}_{-0.47}$. If we impose $s_1 = -0.5$, then $s_2 = -1.49^{+0.71}_{-0.49}$. The large uncertainties are due to the small number of hosts in this sample. DTDs with a break, such as $-1/-2$, underpredict the SN Ia rates over most of the color range considered; the observed SNe Ia are more concentrated in the RS than these steeper models predict. As noted above, a DTD model with a strong cutoff is ruled out at the $>99.99\%$ confidence level. Our results are marginally in agreement with Sand et al. (2012), who obtain a single power-law of $-1.62 \pm 0.54$ under the assumption that early type galaxies formed in a single burst at high redshifts, and have passively evolved since then.

### 6.2. SDSS

The $\Delta(g - r)$ analysis is shown in Figure 7. The most likely model is, for constant power-law slope, $s_1 = s_2 = -1.50^{+0.19}_{-0.15}$, alternately, if $s_1 = -1$, then $s_2 = -1.69^{+0.26}_{-0.24}$, and if $s_1 = -0.5$, then $s_2 = -1.84^{+0.28}_{-0.25}$. This sample, which exhibits the smallest uncertainties, suggests a slightly steeper DTD. The $s_1 = -0.5/s_2 = -1$ and $s_1 = s_2 = -1$ DTDs overpredict SNe Ia at the red end, causing the slope of the predicted curves to increase more steeply than the observations. The opposite trend is observed with the $-1/-2$ and $-1/-3$ models.

The results for $\Delta(u - r)$ indicate that a somewhat shallower DTD is preferred: $s_1 = s_2 = -1.31^{+0.15}_{-0.28}$ or $s_1 = -1$, $s_2 = -1.4^{+0.55}_{-0.40}$, or $s_1 = -0.5$, $s_2 = -1.54^{+0.58}_{-0.42}$. We note that the RS is less obvious in the $u - r$ color, mainly because of the larger uncertainties in the $u$ filter.

We have tried removing the supernovae in the faintest hosts in Figures 7 and 8. The conclusions remain unchanged.

### 6.3. SDSS Stretch Analysis

It has been known since the pioneering work of Phillips (1993) that the width of SN Ia light curves correlates with peak absolute magnitude. The shape of SN Ia light curves in rest-frame $g$ or $B$ light can in fact be matched using a simple scaling of the time axis (Astier et al. 2006); the time scaling factor is the “stretch” parameter $s$ or $s_1$. (See Guy et al. 2010 for the relation between these two quantities.) Sullivan et al. (2006) showed that there is a strong dependence of stretch on host

---

**Table 2**

| Sample     | $s_1$ | $s_1$ | $s_1$ |
|------------|-------|-------|-------|
| MENeaCS    | $-1.26^{+0.57}_{-0.33}$ | $-1.35^{+0.66}_{-0.47}$ | $-1.49^{+0.71}_{-0.49}$ |
| SDSS ($g - r$) | $-1.50^{+0.19}_{-0.15}$ | $-1.69^{+0.26}_{-0.24}$ | $-1.84^{+0.28}_{-0.25}$ |
| SDSS ($u - r$) | $-1.31^{+0.28}_{-0.28}$ | $-1.4^{+0.55}_{-0.40}$ | $-1.54^{+0.58}_{-0.42}$ |
galaxy color (i.e., stellar population mix), in the sense that redder galaxies host lower stretch SNe Ia.

We obtained the stretch parameter $x_1$ for many of the SNe Ia in our SDSS sample from the latest release of the SDSS-II SN survey (Sako et al. 2014), and transformed these values to $s$. We compare the cumulative distribution of the high ($s > 1$) and low ($s < 1$) stretch subsamples with predictions from the SDSS spectroscopic control sample in $g - r$, as shown in Figure 10. As we have already seen, a single DTD, with no cutoff and power law index of $\sim -1.5^{+0.15}_{-0.12}$, can explain the “All” hosts curve. However, each SN Ia stretch sample can be represented by a distinct DTD. While low stretch SNe are described by a continuous power law of index $-1.27^{+0.27}_{-0.35}$, high stretch SNe are better explained by a DTD that exhibits a break or a cutoff. Although a KS test between the low and high stretch SNIa host galaxies cannot rule out at a significant level that both samples were drawn from the same underlying distribution, we do find that the late-time slopes are significantly different at the 1\sigma level (using the Poisson statistics in Section 5). Specifically, for models with $s_1 = -1$ (i.e., the purple, magenta, brown, and yellow lines in Figure 10), we find that for the low stretch sample $s_2 = -1.35^{+0.35}_{-0.51}$, and for the high stretch sample $s_2 = -2.35^{+0.40}_{-0.38}$. We furthermore note that although the curve of the cumulative $P$ distribution for the high stretch sample in Figure 10 has a different shape than the other samples and models, this is not a worry because the difference is caused by a dearth of red host colors, which is fundamentally consistent with a late-time cutoff in the DTD. The interpretation of a difference in the DTD for low/high stretch SNe Ia is discussed further in Section 7.

7. DISCUSSION

Figure 11 shows the agreement of models and data for different cutoff slopes (using the SDSS data in $g - r$ and assuming $s_1 = -1$). The most important conclusion is that DTD models with a drastic cutoff ($-1/\infty$) can be excluded, while models with a break ($s_1 = -1$, $s_2 < -2.15$) are unlikely at 95% confidence level. As discussed in Section 1, this appears to be inconsistent with many formulations of the SD scenario, but more or less consistent with the DD scenario (e.g., Greggio 2005). Increasing the cutoff age $t_c$ adds SNe at later times (see Figure 11), and possibly improves the agreement with the SD model. If $t_c = 2 \times 10^8$ yr, then the best model is $s_1 = -1$, $s_2 = -1.91^{+0.36}_{-0.33}$ (SDSS in $g - r$); but DTDs with a cutoff ($-1/\infty$) are still excluded at >99.7% confidence.

The power-law slope of a continuous DTD that accounts for the rate observed in old galaxies ($> 1$ Gyr) must be around $-1.5$ for our best sample (SDSS $g - r$); this is because of the presence of SNe Ia in RS galaxies in significant numbers. The other data samples (SDSS $u - r$ and MENeACs) are consistent with this result; there are several reasons that this power-law may differ from the canonical $r^{-1}$ often quoted for the DD scenario from gravitational radiation energy losses. A DTD $\propto r^{-1}$ is derived using a distribution of initial orbital separations $\propto a^{-1}$ (Maoz & Mannucci 2012); but this distribution of $a$ is poorly known. A bigger problem is the distribution of orbital separations emerging from the common envelope phase—this distribution is not necessarily $a^{-1}$, nor need it be a power-law. A final problem is that the relevant time for the DTD is the sum of both the gravitational energy loss timescale and the evolutionary timescale of the secondary star.

As already discussed (Section 4.3), our results are only weakly sensitive to assumptions regarding SFH. Nor are our conclusions dependent on the stellar population modeling. In Section 4.4 we showed that our analysis is independent of EHB fraction, metallicity, and age parameters; we also found similar
results with a different population synthesis code. At least part of this insensitivity is a consequence of measuring all colors differentially with respect to the oldest stellar populations.

Our tentative interpretation that SNe Ia are dominated by DD events depends on whether there is a cutoff in the DTD for the SD scenario. This cutoff is predicted from constraints on the mass of the primary (see Section 1). However, the findings of Moe & Di Stefano (2015) challenge this picture by introducing a new class of binaries with extreme mass ratios, potentially leading to more SD SNe Ia at longer delay times. This is because the more massive star in such a binary would quickly evolve into a CO-WD, but the low mass secondary would stay in the MS phase for several Gyr before mass transfer starts. A modified DTD including these binaries is yet to be computed, and it is unclear what the expected DTD shape past 1–2 Gyr would be. Nevertheless, the possible existence of these binaries could affect our conclusions.

Subsampling by stretch parameter s for the SDSS SNe, we found that low stretch SNe Ia can be well represented by a DTD with a continuous power-law slope $-1.27_{-0.27}^{+0.43}$, whereas the high stretch sample requires a cutoff. A similar result has been found by Brandt et al. (2010) who employed the VERSatile SPectral Analysis code (Tojeiro et al. 2007) to infer the SFH of each galaxy based on its spectrum. This result was to be expected, given that low (high) stretch SNe Ia are predominantly found in red (blue) galaxies (Sullivan et al. 2006; Lampeitl et al. 2010; Smith et al. 2012). Yet the idea of multiple SN Ia paths is long-standing (e.g., Branch 1998), and there is independent evidence for the existence of two or more classes of SNe Ia (e.g., Brandt et al. 2010; Wang et al. 2013; Childress et al. 2015). One simple interpretation of our results is therefore that the DD channel explains the low stretch SNe, while the SD channel may reproduce the brighter SNe. (See below for a discussion of other channels.)

While the idea of two SN populations is a tantalizing explanation of the stretch-SDT dichotomy, it should however be pointed out that this model is not demanded by the data. As an example of a single progenitor model, consider the effect of WD mass, which is higher in younger (bluer) populations. If WD mass is correlated with the brightness of the explosion, ejecta mass and velocity, then the observed correlations might arise naturally, without the need for two SN Ia channels.

We have interpreted our results only in terms of the SD and DD scenarios; the DTDs of other channels are not as well known. For the core degenerate (CD) channel, in which a WD merges with the core of an AGB star, an SN Ia might result during or shortly after the common-envelope phase (Livio & Riess 2003). In this case, the CD scenario would be able to explain SNe Ia only in star-forming galaxies (Ilkov & Soker 2013), given that the companion AGB star is required to be massive (Livio & Riess 2003; Kashi & Soker 2011).

However, if the SN Ia explosion event is delayed because of the effects of rapid rotation, then the time delay necessary to spin down the object via magneto-dipole radiation would allow populations as old as 10 Gyr to host SNe Ia (Ilkov & Soker 2012).

Ruiter et al. (2011) investigated the DTD of the sub-Chandrasekhar double detonation channel and concluded that it has two distinct components. The first component exhibits short delay times ($\lesssim$500 Myr) and is derived assuming a non-degenerate He-star donor (resembling the SD scenario). The second component includes long delay times, from $\sim$1 to 10 Gyr, and is derived from an He WD donor (thus resembling the DD scenario). In general terms, such a DTD is consistent with our observations and models. (It is, however, a concern that the Ruiter et al. 2011 DTD has a power slope of $-2$ at $t \gtrsim 1$ Gyr, which only marginally agrees with our results.)

8. SUMMARY

The specific supernova type Ia rate per unit r-band luminosity, sSNR$_L$, exhibits a host galaxy color dependence that is strongly sensitive to the assumed SN Ia DTD, but that is insensitive to SFH. This result occurs because of a fine balance between age, color and $M/L$ effects. For a power-law DTD $\propto t^{-1}$ (as expected for the DD channel), sSNR$_L$ is nearly independent of both galaxy color and stellar population mixture.

We have compared observations of the color distributions of SN Ia hosts with the predictions of simple models. We conclude that a continuous DTD with a power-law slope in the range $-1.3$ to $-1.7$ provides a good match between models and observations; a strong cutoff in the DTD for $t \gtrsim 1$ Gyr is excluded, implying that a weak “frosting” of young stars is insufficient to account for the comparatively large SN rate in the RS. This result is supportive of the DD channel for SN Ia progenitors although our most likely models deviate from the canonical power-law $t^{-1}$ predicted for this channel. We note, however, that this prediction depends on poorly known quantities, such as the distribution of orbital separations emerging from common envelope phase.

Low stretch (fast) supernovae are better fitted by a DTD with a continuous power-law slope $-1.27_{-0.27}^{+0.43}$, whereas high stretch (slow) SNe Ia more closely match the predictions of a DTD with a break or a cutoff. This result may be indicative of two progenitor classes; other interpretations are however possible.

Larger control and host samples will allow a better contrast between observations and the predictions of different DTDs. For example, relaxing the spectroscopic redshift requirement for the SDSS samples would increase the number of supernovae by an order of magnitude.

Further modeling is needed if we are to compare observations with a wider range of progenitor scenarios; in particular, we lack predicted DTDs for the CD and sub-Chandrasekhar models. Moreover, as already noted in Section 1, the plethora of DTDs predicted for the SD channel are in strong disagreement with each other. We again highlight the possible effects of high mass ratio binaries on the shape of the SD DTD. In light of these and other complications, the interpretation of our results remains uncertain: we have good constraints on the power-law slope and (lack of a) cutoff for the DTD, but the meaning of these results in terms of progenitor scenarios is less clear.

Finally, we plan to investigate the applicability of the color–sSNR$_L$ relation to more complex SFHs, and include other parameters in its formulation. This would allow one to utilize the full color range of SN Ia hosts, consequently enlarging the control and host samples.

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