How old are SN Ia progenitor systems? New observational constraints on the distribution of time delays from GALEX

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ABSTRACT
The time delay between the formation of the progenitor systems of Type Ia supernovae (SNe Ia) and their detonation is a vital discriminant between the various progenitor scenarios that have been proposed for them. We use Sloan Digital Sky Survey optical and Galaxy Evolution Explorer (GALEX) ultraviolet observations of the early-type host galaxies of 21 nearby SNe Ia and quantify the presence or absence of any young stellar population to constrain the minimum time delay for each supernova. We find that early-type host galaxies lack ‘prompt’ SNe Ia with time delays of $\lesssim 100$ Myr and that $\sim 70\%$ SNe Ia have minimum time delays of $275$ Myr–$1.25$ Gyr, with a median of $650$ Myr, while at least $20\%$ SNe Ia have minimum time delays of at least $1$ Gyr at $95\%$ confidence and two of these four SNe Ia are likely older than $2$ Gyr. The distribution of minimum time delays observed matches most closely the expectation for the single-degenerate channel with a main sequence donor. Furthermore, we do not find any evidence that subluminous SNe Ia are associated with long time delays.

Key words: supernovae: general – galaxies: elliptical and lenticular, cD – ultraviolet: galaxies.

1 INTRODUCTION
The progenitor channels of Type Ia supernovae (SNe Ia) are of vital importance both to our understanding of stellar evolution and to modern cosmology where SNe Ia are used as standard candles (Riess et al. 1998; Perlmutter et al. 1999). They are also a key part of our understanding of galaxy formation by the virtue of their contribution to the energy budget and chemical evolution of their host galaxies (e.g. Greggio & Renzini 1983; Matteucci & Greggio 1986; Pipino & Matteucci 2004). A range of recent observations have indirectly suggested that at least some SNe Ia can be produced by a variety of different progenitor systems, though these claims are tentative (Hansen 2003; Ruiz-Lapuente et al. 2004; Patat et al. 2007; Voss & Nelemans 2008; Justham et al. 2009). Since no SN Ia progenitor system has been conclusively identified pre-explosion, we must use more indirect approaches to understand their origin.

The various progenitor scenarios proposed in the literature have very different predictions for the time delay between the episode of star formation producing progenitor systems, and the time until the detonation of SNe Ia and so observational constraints on the distribution of time delays (DTD) are thus critical for discriminating between the various scenarios. We will discuss each of them in turn.

1.1 Progenitor scenarios for SN Ia and their expected time delays
Theory proposes that there are two main scenarios for the origin of SNe Ia; in both cases, the system giving rise to the SN Ia is the thermonuclear explosion of a Carbon–Oxygen (CO) white dwarf (WD) in a binary system. We briefly describe the main channels here; for a full review of progenitor scenarios and explosion mechanisms, see Podsiadlowski et al. (2008).

1.1.1 Single degenerate scenarios
In the single degenerate scenario (SD), the steady mass transfer from a main sequence (MS) donor star slowly builds the mass of a WD companion until it reaches approximately the Chandrasekhar mass,\(^1\) initiating an SN Ia (Nomoto & Kondo 1991; Hachisu, Kato & Nomoto 1999; Langer et al. 2000; Han & Podsiadlowski 2004; Justham et al. 2009). By the time of explosion, the donor can already be a slightly evolved subgiant. In this scenario, the time delay distribution is expected to peak at $\sim 670$ Myr with virtually no contribution past $\sim 1–1.5$ Gyr (Han & Podsiadlowski 2004).

Both very short (or ‘prompt’) and very long $\sim 1$ Gyr time delay for SD channels have been proposed: Hachisu, Kato & Nomoto 1999; Langer et al. 2000; Han & Podsiadlowski 2004; Justham et al. 2009).

\(^1\) The point at which an explosive nuclear runaway occurs in a non-rotating CO WD may be slightly below the Chandrasekhar mass. Nomoto, Thielemann & Yokoi (1984) calculate a value of $\sim 1.378 M_\odot$.\n
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(2008) suggest that massive (6–7 M⊙) MS donors are viable, while Wang et al. (2009) argue for Helium star donors. In both cases, the detonation is expected to occur within ≲100 Myr. Very long SD time delays are possible if the donor is a low-mass red giant (RG) (Hachisu & Nomoto 1996; Hachisu et al. 1999).

1.1.2 Double degenerate scenarios
In the double-degenerate channel (DD) on the other hand, the thermonuclear explosion occurs when two WDs in a binary system merge (Iben & Tutukov 1984; Webbink 1984). The range of possible time delays is set by the time-scale for the formation of a WD binary system followed by the time needed for orbital decay via gravitational waves (Shapiro & Teukolsky 1983), which depends only on the binary separation following the common envelope phase.

1.2 Early-type galaxies as an ideal laboratory
Recent advances in our understanding of star formation – and absence thereof – in the local early-type population, together with a large volume of new observations make early-type galaxies an ideal laboratory for constraining the time-delay distribution of low redshift SNe Ia. Local early-type galaxies have generally been considered to have formed at high redshift and devoid of any current or recent star formation (e.g. Bower, Lucey & Ellis 1992; Thomas et al. 2005), implying that any SN Ia progenitor systems are old with ages of several Gyrs. This view has been revised in recent years by observations from the Galaxy Evolution Explorer (GALEX; Martin et al. 2005) ultraviolet (UV) space satellite: Yi et al. (2005) found that a substantial fraction of early-type galaxies observed by GALEX had UV-optical colours incompatible with any scenarios of enhanced extreme horizontal branch stars (UV upturn; for a review of the current state see Yi 2008) that could only be explained by the presence of small young stellar populations.

This discovery was quantified using UV-optical colours to determine that between 1/3 and half of the local luminous early-type galaxy population harboured young stellar populations with mass fractions of a few percent and ages up to approximately 1 Gyr (Kaviraj et al. 2007; Schawinski et al. 2006, 2007a) and their presence has been detected out to z ≈ 1 (Kaviraj et al. 2008).

The inclusion of the GALEX near- and far-UV broad-band photometry (NUV, 1771–2831 Å; FUV, 1344–1786 Å; Morrissey et al. 2007) into the optical spectral energy distribution allows us to detect and quantify any young stellar populations in terms of age and mass fraction, or to rule out their presence against the backdrop of an old, passively evolving bulk stellar population. This makes early-type galaxies in the local universe observed by GALEX an ideal laboratory to constrain and quantify the ages of SN Ia progenitors for those events which occurred in early-type galaxies. Late-type galaxies with extended star formation histories are not suitable for constraining time delays out to interesting ages, as they always harbour stars of very young ages from ongoing star formation.

1.3 Previous constraints on SN Ia time delays
Previous studies have endeavoured to determine the DTD of SNe Ia and connect them to progenitor scenarios. On the theory side, analytical calculations by Greggio (2005) and Belczynski, Bulik & Ruiter (2005) argue that the SD channel with short time delays is unlikely to account for all SNe Ia in passive systems. Similarly, Pritchett, Howell & Sullivan (2008) make the case that the SD channel alone can only account for the observed relationship between the SNe Ia rate and host galaxy star formation rate under unrealistic assumptions. Similarly, Strolger et al. (2004, 2005) and Förster et al. (2006) attempted to reconstruct the DTD from the cosmic star formation history, but they concluded that this approach is limited by uncertainties in the star formation history (SFH). In addition, the small sample statistics of Strolger et al. (2004, 2005) are a further limiting factor.

The properties of SNe Ia depend on the properties of their host galaxies. The brighter, slowly declining events tend to occur in star-forming host galaxies, while the dimmer, more rapidly declining SNe Ia are preferentially found in red, passive host galaxies (see e.g. Sullivan et al. 2006). This has led to the hypothesis that the bright SNe Ia result from progenitor systems with short time delays in star-forming galaxies, while the dimmer events, hosted by galaxies without any current or recent star formation are due to scenarios with longer time delays. Mannucci, Della Valle & Panagia (2006) argued for the existence of two separate SN Ia populations, a ‘prompt’ component with a time delay of ≈100 Myr, and a ‘delayed’ component with time delays of 3–4 Gyrs. Botticella et al. (2008) and Totani et al. (2008) have analysed the host galaxies of SNe Ia and concluded that a substantial fraction of SNe Ia must have long time delays on the order of 2–3 Gyrs. At the other end of the delay time range, Aubourg et al. (2008) have argued that there is a subpopulation of SNe Ia with very short time delays of less than 180 Myr.

Gallagher et al. (2008) recently argued to have found a direct link between the properties of individual SNe Ia and the bulk stellar populations of early-type host galaxies. They claim that that SNe Ia in host galaxies with older bulk ages and higher metallicities are dimmer and decay more rapidly. This has however been disputed by Howell et al. (2009) who find no such correlation. The tempting conclusion to draw here is that perhaps subluminous SNe Ia (sometimes called 1991bg-like, after the prototypical event) are from the long-time delay population, perhaps originating from a different explosion mechanism due to their progenitor channel (e.g. Howell 2001; Taubenberger et al. 2008; Howell et al. 2009).

The consensus in the literature is that subluminous events are due to explosions with low 56Ni masses (e.g. Höflich et al. 2002; Fesen et al. 2007).

Rather than infer time delays indirectly from the bulk stellar population via optical data, in this paper we probe deeper into the star formation history of a sample of 21 SN Ia host galaxies and use GALEX UV data to determine the presence or absence of minor episodes of recent star formation and thus constrain the minimum time delay for these SNe Ia.

This paper is organized as follows. In Section 2, we discuss the selection of early-type SN Ia host galaxies that have been observed by GALEX and compare them to the general population. In Section 3, we motivate and describe our spectral energy distribution (SED) analysis method and present the results from applying it in Section 4, followed by a discussion in Section 5. We assume cosmological parameters (Ωm = 0.3, ΩΛ = 0.7, H0 = 70), consistent with the Wilkinson Microwave Anisotropy Probe (WMAP) third-year results and their combination of results with other data (Spergel et al. 2007).

2 SAMPLE SELECTION

2.1 SN Ia early-type host galaxies
We take the catalogue of visually inspected early-type galaxies that have hosted an SN Ia presented by Förster & Schawinski (2008).
The objects in this sample were culled by visually inspecting all host galaxies of SN Ia from the Center for Astrophysics (CfA) list of supernovae\(^1\) that overlap with the Sloan Digital Sky Survey DR6 (SDSS; Adelman-Mccarthy et al. 2008). The visual classification is vital to avoid the inclusion of systems with weak discs or spiral arms that can contaminate selections by proxies such as structural parameters or optical colours (see e.g. Schawinski et al. 2007b; Lintott et al. 2008). We then limit this to those objects with observations in the GALEX GR4 archive\(^2\), regardless of the survey; in total, this leaves us with a sample of 21 objects (see Table 1). We did not require a GALEX detection, only an observation, to avoid a bias towards UV-bright objects; however, all objects in our sample have a detection in at least one GALEX filter.

Where GALEX data at multiple depths was available, the deeper image was used. The optical SDSS host galaxy and the corresponding GALEX detection were matched by hand.

### 2.2 Are SN Ia host galaxies different from normal early-type galaxies

Before we begin our quantitative analysis of the recent star formation histories of the SN Ia host galaxies, we compare their UV-optical properties to those of normal early-type galaxies. For comparison, we use the sample of early-type galaxies with GALEX observations presented in Schawinski et al. (2007a). This sample is magnitude-limited (\(r < 16.8\)), limited to \(0.05 < z < 0.1\) and visually inspected for early-type morphology. We must preface this comparison by pointing out that while this comparison sample is well-defined, the SN Ia host galaxies sample is not; it is drawn from a heterogeneous parent sample of SN Ia composed of various surveys, all with their own selection effects and serendipitous discoveries of individual supernovae. Keeping this caveat in mind, we proceed to compare the two.

In Fig. 1, we show the \(NUV - r\) colour–magnitude diagram for the SN Ia host galaxies (black points) and the comparison sample from Schawinski et al. (2007a) (grey points). The comparison sample reasonably covers the parameter space of the SN Ia host galaxies. The host galaxies of SN2005dh and SN2005bm are both very blue in \(NUV - r\) and very luminous. We compare the \(NUV - r\) colour distributions of the host galaxies and the comparison sample in Fig. 2. While the cumulative distribution of the host galaxies might appear to indicate a lack of host galaxies at the bluest \(NUV - r\) colour, both a Kolmogorov–Smirnov and a Kuiper test indicate that the two distributions are consistent with being drawn from the same parent distribution, and so this lack of very blue SN Ia hosts is not statistically significant at the 95 per cent level.

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1. Spectrum resembles SN1991bg (Filippenko & Chornock 2003), potentially subluminous.
2. Faintest SN Ia known (Kasliwal et al. 2008).
3. Reported subluminous by Blondin et al. (2007).

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### Table 1. The sample of SNe Ia and their host galaxy properties.

| Galaxy name | Supernova name | Redshift | \(NUV - r\) (mag) | \(M_r\) (mag) | Best-fitting young age \(t_y\) (Myr) | Young age range (Myr) | Youngest possible \(t_y\) at 68 per cent confidence (Myr) | Youngest possible \(t_y\) at 95 per cent confidence (Myr) |
|-------------|----------------|----------|-----------------|-------------|--------------------------------|----------------------|-------------------------------------------------|-------------------------------------------------|
| NGC4493     | SN1994M        | 0.02316  | 5.69 ± 0.15     | -21.61 ± 0.002 | 684                             | 650–1980             | 719                                                  | 558                                                  |
| CGCG169-00  | SN2002di       | 0.03639  | 5.57 ± 0.13     | -21.98 ± 0.002 | 881                             | 926–6670             | 1193                                                 | 757                                                  |
| IC4258      | SN2003an       | 0.03704  | 6.22 ± 0.13     | -22.36 ± 0.002 | –                                | –                     | 6028                                                  | 2550                                                  |
| NGC6095     | SN2003au\(^1\) | 0.03084  | 5.96 ± 0.07     | -22.74 ± 0.002 | 587                             | 531–650              | 558                                                  | 480                                                  |
| NGC6109     | SN2003al       | 0.02954  | 5.87 ± 0.11     | -22.40 ± 0.002 | –                                | –                     | 2424                                                  | 1025                                                  |
| CGCG044-04  | SN2004bj      | 0.05015  | 5.68 ± 0.17     | -23.20 ± 0.002 | 757                             | 757–7764             | 926                                                  | 650                                                  |
| NGC4493     | SN2004br       | 0.02316  | 5.69 ± 0.15     | -21.61 ± 0.002 | 684                             | 650–1980             | 719                                                  | 558                                                  |
| CGCG089-05  | SN2004gs      | 0.02664  | 5.26 ± 0.04     | -21.57 ± 0.002 | 618                             | 513–684              | 505                                                  | 480                                                  |
| IC0708      | SN2004h        | 0.03168  | 5.73 ± 0.05     | -22.64 ± 0.002 | –                                | –                     | 4021                                                  | 1255                                                  |
| 2MASXJ1520  | SN2005bm      | 0.10350  | 4.25 ± 0.11     | -22.92 ± 0.003 | 587                             | 433–618              | 505                                                  | 336                                                  |
| MRK0993     | SN2005dh       | 0.03836  | 4.57 ± 0.03     | -22.98 ± 0.002 | 618                             | 531–837              | 587                                                  | 480                                                  |
| 2MASXJ0141  | SN2005ex       | 0.09000  | 4.66 ± 0.13     | -21.18 ± 0.006 | 456                             | 336–531              | 392                                                  | 275                                                  |
| 2MASXJ0134  | SN2005js      | 0.07968  | 6.19 ± 0.33     | -21.59 ± 0.004 | 587                             | 433–618              | 505                                                  | 372                                                  |
| 2MASXJ0110  | SN2005kt      | 0.06540  | 5.08 ± 0.10     | -21.00 ± 0.004 | 684                             | 650–1389             | 719                                                  | 587                                                  |
| CGCG193-01  | SN2006bk      | 0.04953  | 5.89 ± 0.05     | -23.46 ± 0.002 | 618                             | 558–650              | 587                                                  | 505                                                  |
| NGC3841     | SN2006eq      | 0.02120  | 5.11 ± 0.04     | -21.14 ± 0.002 | 837                             | 719–1320             | 796                                                  | 684                                                  |
| CGCG294-03  | SN2007ar       | 0.05293  | 6.06 ± 0.13     | -22.89 ± 0.002 | –                                | –                     | 4449                                                  | 796                                                  |
| NGC2577     | SN2007ax\(^2\) | 0.00686  | 5.49 ± 0.04     | -20.30 ± 0.002 | 757                             | 757–6028             | 837                                                  | 650                                                  |
| CGCG077-10  | SN2007cf\(^3\) | 0.03293  | 5.60 ± 0.07     | -21.41 ± 0.002 | –                                | –                     | 1537                                                  | 975                                                  |
| 2MASXJ1410  | SN2007ei      | 0.10000  | 5.77 ± 0.46     | -22.04 ± 0.005 | –                                | –                     | 1461                                                  | 837                                                  |
| CGCG391-01  | SN2007jh      | 0.04080  | 7.08 ± 0.42     | -22.32 ± 0.002 | –                                | –                     | 4021                                                  | 2191                                                  |

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1. Old age
2. Young age
3. Metallicity
4. Dust extinction
5. Young mass fraction

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### Table 2. Model parameters.

| Parameter                      | Range       |
|-------------------------------|-------------|
| Old age \(t_o\)               | 1–15 Gyr    |
| Young age \(^1\) \(t_y\)      | 0.1–15 Gyr  |
| Metallicity \(Z\)             | \(\frac{1}{\text{Z}_{\odot}}\)–3.25 \(\text{Z}_{\odot}\) |
| Dust extinction \(^2\) \(E(B-V)\) | 0–0.3      |
| Young mass fraction \(^2\) \(f_y\) | 1–100 per cent |

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1. The young age \(t_y\) is always restricted to be less than the old age \(t_o\).
2. We use a Calzetti et al. (2000) extinction law.

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\(^2\) http://www.cfa.harvard.edu/iau/lists/Supernovae.html

\(^3\) http://galex.stsci.edu/GR4/
Figure 1. The UV-optical colour–magnitude relation of a sample of normal early-type galaxies, and the SN Ia host galaxies examined in this work. The grey points are the comparison sample of early-type galaxies taken from Schawinski et al. (2007a), while the black points are the SN Ia host galaxies with GALEX observations from Förster & Schawinski (2008). For the SN Ia host galaxies, we show the error bars on the $NUV - r$ colour; these are dominated by the error on NUV. We also label each host galaxy by the name of the supernova that occurred (cf. Table 1).

Figure 2. The cumulative $NUV - r$ colour distribution of both the SN Ia host galaxies (solid line) and the comparison sample (dashed line). The two colour distributions are closely matched. There appears to be a lack of very blue SN Ia hosts ($NUV - r < 4$), but neither a Kolmogorov–Smirnov test nor a Kuiper test indicate that the two populations are drawn from a different parent distribution; the lack of very blue SN Ia hosts is thus not statistically significant.

3 METHOD

3.1 Quantitative analysis of the recent star formation history

The exquisite sensitivity of the near-UV to small amounts of young stellar populations makes it the ideal tool to quantify any young populations or to rule out their presence down to very small levels. The old bulk stellar populations of massive early-type galaxies make the exercise of measuring small young components easier. In Fig. 3 (left-hand panel), we show the evolution of the $NUV - r$ colour as a function of the age of the young component for a range of parameters to illustrate the strong age sensitivity of $NUV - r$. On the right-hand panel, we show a composite SED of a single 12 Gyr old burst (red) and a 800 Myr young burst of a 1 per cent mass fraction (blue). While it hardly changes the total SED (green) in the optical wavelengths probed by SDSS, the young population dominates the UV wavelengths probed by GALEX.

We parametrize the star formation history as two components: a burst on top of an old component. This parametrization has been successfully implemented before in order to answer questions of galaxy formation (Ferreras & Silk 2000; Kaviraj et al. 2007; Schawinski et al. 2007b, 2009). Any young stellar population, even if small, is luminous compared to the underlying older population. Therefore, by marginalizing over all possible star formation histories before the most recent episode of star formation, we are able to constrain it, usually out to ages of $\sim 1$ Gyr and rule out any such episodes out to 1–2 Gyr.

The properties of any young component are degenerated with a number of other parameters. Factors include the metallicity $Z$, which must be varied over the entire plausible range of metallicities, and should include an internal metallicity distribution with a tail ranging to very low metallicities. For old ages, both the low metallicity tail (Park & Lee 1997; Maraston & Thomas 2000) and high metallicities can contribute moderate UV flux (Yi, Demarque & Kim 1997a; Yi, Demarque & Oemler 1997b). Since we do not wish to erroneously attribute any weak UV flux to young stars, we must account for this alternate, old origin. The availability of far-UV data from the GALEX FUV filter aids somewhat in the differentiation, as these old populations tend to be hotter than young populations of a few hundred Myr and so have a steeper rising UV spectrum. We model our internal metallicity distribution on the observed distribution of the bulges of nearby galaxies (Harris, Harris & Poole 1999; Harris
We generate a library of photometric data points as a function of the parameters described above, resulting in 6.5 million model SEDs in the rest-frame of each SN Ia host galaxy using the models of Maraston (2005, 1998). We fit each host galaxy to all library SEDs and compute the \( \chi^2 \) statistic for each, convert them to probabilities, and marginalize over all parameters except for the young age \( t_y \) in order to obtain the probability distribution function \( P(t_y) \). In order to account for unknown systematic errors in the SDSS and GALEX zero-points and other effects, we add in quadrature a uniform error of 0.1 mag to each band.

We have tested the effect of adding various amounts of systematic error to broad-band photometry for similar codes in general, and for the data set and specific implementation used in this paper. By increasing the amount of assumed systematic error, the minimum set of parameters \( (t_y, f_y) \) does not change and individual fits do not change from cases where a young population is detected to one where a young population is ruled out. Increasing the assumed error increases the size of the errors on \( (t_y, f_y) \) at the minimum or lowers the limit on \( t_y \) in cases where no young component is detected. While the SDSS photometric system is exquisitely calibrated, down to the 1–3 per cent level for DR6,\(^6\) the photometric repeatability of GALEX is \( \sim 0.03 \) and 0.05 mag in NUV and FUV, respectively (Morrisey et al. 2007). Given this, we believe a 0.1 mag error may be a conservative overestimate. We note that the main driver in detecting and ruling out the presence of young stellar populations are UV-optical colours whose observed range spans 5–7 mag, substantially larger than the 0.1 mag error.

4 RESULTS

We present the results of our SED fitting analysis in Figs 4 and 5 and Table 1. For each supernova and host galaxy in our sample, we plot the marginalized probability distribution function \( P(t_y) \) from 100 Myr to 15 Gyr. The supernova host galaxies in our sample can be divided into two classes: those where a small young stellar populations with ages of \( \lesssim 1 \) Gyr, are present, and those where any such young population is ruled out down to 1 per cent by mass

\( \text{SN Ia time delays} \quad 721 \)

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4 The measured range of \( E(B - V) \) for passively evolving early-types is very low; see e.g. fig. 11 in Schawinski et al. (2007b).

5 In one case, the SDSS spectroscopic target selection algorithm selected two off-nucleus positions.

6 See http://www.sdss.org/dr6/ and Adelman-McCarthy et al. (2008).
722 K. Schawinski

Figure 4. The probability distribution functions $P(t_Y)$ characterizing the age of the most recent episode of star formation for those SN Ia host galaxies in our sample where a young component is resolved. We label each panel by the name of the supernova and its host galaxy. Note that SN1994M and SN2004br both occurred in NGC4493, so the $P(t_Y)$ is identical. The black dashed line indicates the best-fitting age, while the single-hatched region shows the two-sided 68 per cent confidence interval.

fraction. This limit corresponds to the age resolution of the near-UV (cf. Fig. 3). For those where a young component is resolved, we can calculate the best-fitting age (Fig. 4), while for those without, we can only report lower limits on the age of the youngest stellar population – and therefore SN Ia progenitor – present (Fig. 5). For comparison, the results for the general early-type population are presented in Kaviraj et al. (2007).

4.1 SNe Ia host galaxies with detected young stellar populations

For 14 out of 21 SN Ia host galaxies in our sample, we do detect and constrain the presence of a small (few percent) young stellar population in the host galaxy. The age of this young population represents the shortest possible time delay for these SNe Ia, though it is of course possible that these particular SNe have longer time delays, up to the age of the bulk stellar population. In Fig. 4, we show $P(t_Y)$ for all 14 host galaxies with resolved young components. In each panel, we indicate the best-fitting age with a dashed black line. We compute the 68 per cent two-sided confidence interval and shade it with single grey hatches. In Table 1, we report the best-fitting ages and the two-sided confidence interval.

4.2 SNe Ia with no detected young stellar populations

For the remaining 7 SN Ia host galaxies, we do not detect the presence of any young stellar population down to the 1 per cent 7 We note that for three of these – SN2002di, SN2004bj and 2007ax – there is a substantial tail to ages of several Gyr and the best-fitting age is around 1 Gyr; these host galaxies straddle the limit of ages that are detectable.
Figure 5. The probability distribution functions \( P(t_y) \) characterizing the age of the most recent episode of star formation for those SN Ia host galaxies in our sample where no young component is resolved. As in Fig. 4, we label each panel by the name of the supernova and its host galaxy. The single-hatched region shows the one-sided 95 per cent confidence limit, while the double-hatched region shows the 68 per cent limit.

level in mass fraction. For these, it only makes sense to compute a one-sided confidence interval. We shade the 68 and 95 per cent confidence limits on the \( P(t_y) \) distribution in Fig. 5 and report these limits in Table 1. We also give these one-sided confidence levels for those host galaxies with detected young components.

At 95 per cent confidence, we find that four SNe Ia (SN2003an, SN2003ia, SN2004H and SN2007jh) have time delays of at least 1 Gyr, with SN2003an and SN2007jh with minimum time delays in excess of 2 Gyr. Given the caveats discussed in Section 3, this implies that long time delays for SNe Ia do occur in nature and at least \( \sim \)20 per cent (4/21) of SNe Ia in early-type host galaxies have time delays longer than 1 Gyr. Due to the inclusion of GALEX observations, the robustness of this statement is greater than that of any previous attempts to establish long time delays for some SNe Ia.

5 DISCUSSION

5.1 The distribution of minimum time delays for SN Ia

We are now able to plot the distribution of minimum time delays (DmTD) for SNe Ia that occurred in early-type host galaxies. In Fig. 6, we plot the histograms of the DmTD for SNe Ia at the 95 per cent limit. The minimum age distribution ranges from 275 Myr to 1.25 Gyr, with two SNe at \( \sim \)2 Gyr and has a mean age of 650 Myr. There are no cases where ages approaching \( \sim \)100 Myr or below are allowed, so it appears that there are no 'prompt' SNe Ia in our sample.\(^8\)

\(^8\)The definition of what constitutes a 'prompt' time delay varies somewhat in the literature. While a value of \( \sim \)100 Myr is common, others are also used. For example Sullivan et al. (2006) use 500 Myr. By their definition, a number of the SNe Ia studies here would be classified as prompt.

Figure 6. The DmTD for the SNe Ia in our sample. These limits are the one-sided confidence limits derived from the \( P(t_y) \) distributions in Figs 4 and 5 (also given in Table 1). The mean and median age are 800 and 650 Myr, respectively.

5.2 Subluminous SNe Ia?

Several works have remarked that subluminous SNe Ia occur in early-type galaxies (e.g. Howell 2001). Under the assumption that these host galaxies contain only old stellar population, this was taken to be evidence that subluminous SNe Ia have very long time delays on the order of several Gyr (Howell 2001). Although our sample of subluminous SNe Ia is very small, we find that in the case of two subluminous SN Ia, a shorter time delay is possible. Our sample contains three subluminous SNe Ia, SN 2003au, SN2007ax and SN2007cf. Of these, SN2003au and SN2007ax (the faintest SN Ia observed yet; Kasliwal et al. 2008) both are in host galaxies...
with young stellar components, while only SN 2007cf has a 95 per cent lower confidence limit of \(\lesssim 1\) Gyr, that is only one subluminous SN Ia definitely has a long time delay. While this does not prove that subluminous SNe Ia have short time delays, it clearly leaves open the possibility that they do.

5.3 Implications for progenitor channels

What do our results imply for the various proposed progenitor channels? There are two ways we can explore implications of the results in this paper for progenitor channels. We can assume that the bulk of SNe Ia originate from the youngest stellar population present in the host galaxy, rather than from the old bulk population. This assumption implies that the DmTD in Fig. 6 is a good approximation of the true DTD and so we can take the DmTD and compare them to the predictions of various theoretical calculations of delay times. We stress that we cannot directly test with the current data whether this assumption is a good one and it remains plausible that the DmTD does not approximate the DTD well at all and that the young populations detected by GALEX are mostly unrelated to the observed SNe Ia. In the following discussion, we explore what the DmTD implies for progenitor channels of SNe Ia assuming that it closely approximates the DTD.

5.3.1 Short time delay scenarios (\(\lesssim 100\) Myr)

Scenarios that give rise to ‘prompt’ SNe Ia, such as massive MS or Helium star donors (Hachisu et al. 2008; Wang et al. 2009), do not appear to occur in our sample. This is not necessarily obvious, as a few percent of early-type galaxies do have optically blue colours and host sufficiently young stellar populations (Schawinski et al. 2007b), though the sample used in this paper does not contain any such objects.

5.3.2 Intermediate time delay scenarios (100–1000 Myr)

The majority of SNe Ia in early-types have minimum time delays on the order of a few hundred Myr. If we assume that the actual DTD is approximated well by Fig. 6, then the binary population synthesis predictions for the SD MS + CO WD scenario matches the distribution of ages well (see Han & Podsiadlowski 2004).

5.3.3 Long time delay scenario (\(\gtrsim 1\) Gyr)

Regardless of whether Fig. 6 is a good representation of the actual DTD, a minority of SNe Ia must have long time delays in excess of 1 Gyr. The two progenitor channels that might account for these long time delays are the DD channel, can naturally produce such long time delays (Iben & Tutukov 1984; Webbink 1984), and the SD channel with RG donors. Calculations for the rate due to WD+RG progenitor systems predict that they cannot account for all SNe Ia in passive host galaxies (e.g. Yungelson & Livio 1998; Han & Podsiadlowski 2004).

6 SUMMARY

We have used SDSS optical and GALEX UV photometry to measure the minimum time delay for a sample of 21 SNe Ia hosted in local early-type galaxies. We constrain the age, or rule out the presence, of any young stellar population in the host galaxies down to the 1 per cent level by mass. From this, we are able to construct the DmTD for the 21 SNe Ia in our sample. We find as follows.

(i) There are no prompt (\(\lesssim 100\) Myr) SNe Ia in our sample.
(ii) For 14 out of 21 SN Ia host galaxies, we detect and constrain young stellar populations, yielding a range of minimum time delays of 275 Myr to 1.25 Gyr, with a mean of 650 Myr.
(iii) For four out of 21 SN Ia host galaxies, we can rule out the presence of any young stellar populations younger than 1 Gyr, implying minimum time delays longer than that. For two of these, the 95 per cent lower confidence limits rule out any time delays shorter than 2 Gyr.
(iv) Two out of three subluminous SNe Ia occurred in host galaxies with detected (few 100 Myr) young populations. Only one occurred in a host galaxy where young populations (\(\lesssim 1\) Gyr) can be ruled out.

We find that the predictions for the SD MS + CO WD channel (Han & Podsiadlowski 2004) best matches the DmTD for the majority of our sample and that at least four require a scenario allowing for time delays greater than 1 Gyr, such as a RG + CO WD or DD channel. Under the extreme assumption that the DmTD is a good approximation of the true DTD, the SD MS + CO WD channel could account for up to 70 per cent of all SNe Ia in early-type galaxies, though the actual percentage could be much lower in case this assumption is not warranted.

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REFERENCES

Adelman-McCarthy J. K. et al., 2008, ApJS, 175, 297
Aubourg É., Tojeiro R., Jimenez R., Heavens A., Strauss M. A., Spergel D. N., 2008, A&A, 492, 631
Belczynski K., Bulik T., Ruiter A. J., 2005, ApJ, 629, 915
Blondin S., Modjaz M., Kirshner R., Challis P., Peters W., 2007, Central Bureau Electronic Telegrams, 958, 1
Botticella M. T. et al., 2008, A&A, 479, 49
Bower R. G., Lucey J. R., Ellis R. S., 1992, MNRAS, 254, 601
Calzetti D., Armus L., Bohlin R. C., Kinney A. L., Koornneef J., Storchi-Bergmann T., 2000, ApJ, 533, 682
Carollo C. M., Danziger I. J., Buson L., 1993, MNRAS, 265, 553
Davies R. L., Sadler E. M., Peletier R. F., 1993, MNRAS, 262, 650
Filippenko A. V., Chornock R., 2003, IAU Circ., 8085, 2
Fesen R. A., Höflich P. A., Kato M., Nomoto K., 1984, ApJ, 277, 791
Hatchisu I., Kato M., Nomoto K., 1999, ApJ, 522, 487
Hatchisu I., Kato M., Nomoto K., 2008, ApJ, 679, 1390
Han Z., Podsiadlowski P., 2004, MNRAS, 350, 1301
Hansen B. M. S., 2003, ApJ, 582, 915
Harris G. L. H., Harris W. E., 2000, AJ, 120, 2423
Harris G. L. H., Harris W. E., Poole G. B., 1999, AJ, 117, 855
Harris W. E., Harris G. L. H., 2002, AJ, 123, 3108
Höflich P., Gerardy C. L., Fesen R. A., Sakai S., 2002, ApJ, 568, 791
Howell D. A., 2001, ApJ, 551, L93
Howell D. A. et al., 2009, ApJ, 691, 661
Iben J., Tutukov A. V., 1984, ApJS, 54, 335
Justham S., Wolf C., Podsiadlowski P., Han Z., 2009, A&A, 493, 1081
Kasliwal M. M. et al., 2008, ApJ, 683, L29
Kaviraj S. et al., 2007, ApJ, 673, 619
Kaviraj S. et al., 2008, MNRAS, 388, 67
Langer N., Deustchmann A., Wellstein S., Höflich P., 2000, A&A, 362, 1046
Lintott C. J. et al., 2008, MNRAS, 389, 1179
Mannucci F., Della Valle M., Panagia N., 2006, MNRAS, 370, 773
Maraston C., 1998, MNRAS, 300, 872
Maraston C., 2005, MNRAS, 362, 799
Maraston C., Thomas D., 2000, ApJ, 541, 126
Martin D. C. et al., 2005, ApJ, 619, L1
Matteucci F., Greggio L., 1986, A&A, 154, 279
Morrissey P. et al., 2007, ApJS, 173, 682
Nomoto K., Kondo Y., 1991, ApJ, 367, L19
Nomoto K., Thielemann F.-K., Yokoi K., 1984, ApJ, 286, 644
Park J.-H., Lee Y.-W., 1997, ApJ, 476, 28
Patat F. et al., 2007, Sci, 317, 924
Perlmutter S. et al., 1999, ApJ, 517, 565
Pipino A., Matteucci F., 2004, MNRAS, 347, 968
Podsiadlowski P., Mazzali P., Levafrè P., Han Z., Förster, F., 2008, New Astron. Rev., 52, 381
Pritchet C. J., Howell D. A., Sullivan M., 2008, ApJ, 683, L25
Riess A. G. et al., 1998, AJ, 116, 1099
Ruiz-Lapuente P. et al., 2004, Nat, 431, 1069
Sarajedini A., Jablonka P., 2005, AJ, 130, 1627
Schawinski K. et al., 2007a, ApJS, 173, 512
Schawinski K., Thomas D., Sarzi M., Maraston C., Kaviraj S., Joo S.-J., Yi S. K., Silk J., 2007b, MNRAS, 382, 1415
Schawinski K. et al., 2006, Nat, 442, 888
Schawinski K. et al., 2009, ApJ, 690, 1672
Shapiro S. L., Teukolsky S. A., 1983, Black holes, white dwarfs, and neutron stars: The physics of compact objects. Research supported by the National Science Foundation. Wiley-Interscience, New York, p. 663
Spergel D. N. et al., 2007, ApJS, 170, 377
Strolger L.-G. et al., 2004, ApJ, 613, 200
Strolger L.-G. et al., 2005, ApJ, 635, 1370
Sullivan M. et al., 2006, ApJ, 648, 868
Taubenberger S. et al., 2008, MNRAS, 385, 75
Thomas D., Maraston C., Bender R., Mendes de Oliveira C., 2005, ApJ, 621, 673
Totani T., Morokuma T., Oda T., Doi M., Yashuda N., 2008, PASJ, 60, 1327
Trager S. C., Faber S. M., Worthey G., González J. I., 2000, AJ, 119, 1645
Voss R., Nelemans G., 2008, Nat, 451, 802
Wang B., Meng X., Chen X., Han Z., 2009, MNRAS, 395, 847
Webbink R. F., 1984, ApJ, 277, 355
Yi S., Demarque P., Kim Y.-C., 1997a, ApJ, 482, 677
Yi S., Demarque P., Oemler A. J., 1997b, ApJ, 486, 201
Yi S. K., 2008, in Heber U., Jeffery C. S., Napiwotzki R., eds, ASP Conf. Ser. Vol. 392, Hot Subdwarf Stars and Related Objects. Astron. Soc. Pac., San Francisco, p. 3
Yi S. K. et al., 2005, ApJ, 619, L111
Yungelson L., Livio M., 1998, ApJ, 497, 168

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