CONSTRAINING TYPE Ia SUPERNOVAE PROGENITORS FROM THREE YEARS OF SUPERNOVA LEGACY SURVEY DATA

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ABSTRACT

While it is generally accepted that Type Ia supernovae are the result of the explosion of a carbon–oxygen white dwarf accreting mass in a binary system, the details of their genesis still elude us, and the nature of the binary companion is uncertain. Kasen points out that the presence of a non-degenerate companion in the progenitor system could leave an observable trace: a flux excess in the early rise portion of the light curve caused by the ejecta impact with the companion itself. This excess would be observable only under favorable viewing angles, and its intensity depends on the nature of the companion. We searched for the signature of a non-degenerate companion in three years of Supernova Legacy Survey data by generating synthetic light curves accounting for the effects of shocking and comparing true and synthetic time series with Kolmogorov–Smirnov tests. Our most constraining result comes from noting that the shocking effect is more prominent in the rest-frame B than V band: we rule out a contribution from white dwarf–red giant binary systems to Type Ia supernova explosions greater than 10% at the 2σ, and greater than 20% at the 3σ level.

Key words: methods: data analysis – supernovae: general – white dwarfs

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1. INTRODUCTION

Type Ia supernova (SN Ia) explosions are marvelous astrophysical tools, and they currently offer the most precise way of constraining dark energy (Sullivan et al. 2011). Today, several thousand SNe Ia have been observed and theoretical models and simulations are progressing rapidly (see, for example, Almgren et al. 2010), and many aspects of SN Ia explosions can be reproduced in detail. However, these cosmic explosions, studied for decades, are still not fully understood. Particularly, we lack a solid understanding of the progenitor systems. There is a consensus that SNe Ia arise from the thermonuclear explosion of a carbon–oxygen (C–O) white dwarf (WD), but is the WD in a binary system with a main-sequence (MS) or red giant (RG) star, accreting mass from the companion to approach the Chandrasekhar limit (single degenerate—SD—scenario)? Or is the explosion caused by the merger of two WDs in a compact binary system (double degenerate—DD—scenario)? Constraining the progenitor scenarios is key for learning the details of SN Ia explosion physics, and to improve our understanding of the effects of environment on SN Ia explosions and thus of the systematics that still affect the constraints on cosmology derived from SN surveys (Kessler et al. 2009; Guy et al. 2010; Wood-Vasey et al. 2007; for a review of SN Ia cosmology, see Howell 2010).

No progenitor system of an SN Ia has yet been observed prior to explosion; these binary systems would be very faint and undetectable at this time in extra-galactic surveys. Population synthesis and environment studies have not been able to firmly set constraints on the SN Ia progenitors (Iben & Tutukov 1984). From the theoretical point of view, generating SNe Ia in the DD scenario presents difficulties. The mass transfer only successfully leads to a deflagration if it occurs at a rate significantly slower than the Eddington limit, through the formation of a thick disk (Nomoto & Iben 1985), and even then fine-tuning of various parameters might be needed (see Tout 2007 for a brief review, and references therein).

Some observational evidence might already disfavor SD progenitors. While the WD accretes mass from a companion in the SD scenario, the system should emit X-ray radiation for an extended period of time. Under the assumptions of a continuous duty cycle, and that all SD progenitors emit in the X-ray, the SN Ia rate is too high by over an order of magnitude compared to the number of X-ray sources observed in nearby elliptical galaxies (Gilfanov & Bogdán 2010), as well as soft X-ray sources in our own galaxy (Di Stefano 2010a). While this
evidence can be used to set upper limits on SD progenitors, Di Stefano (2010b) points out that there are too few super soft X-ray sources, sources with energy typically 10–100 eV and luminosity 10^{-37} to 10^{-38} erg s^{-1}, to account for the Type Ia rate within the DD scenario as well, suggesting instead that super soft X-ray radiation may not always be emitted in nuclear-burning white dwarf systems and that it could be absorbed within the system itself. A few peculiar SNe Ia have been observed in the past few years to produce 56Ni masses close to, or in excess of, the 1.4 Msolar theoretical limit for a WD mass; the Chandrasekhar limit. These apparent super-Chandrasekhar SNe Ia may originate from the merger of two WDs, in the DD scenario (Howell et al. 2006; Silverman et al. 2011; Yuan et al. 2010).

Kasen (2010, hereinafter K10) explores the effect that a non-degenerate companion star would have on the observables of the explosion, and shows that in the SD scenario, the presence of a companion may manifest itself in the early days after the SN explosion as a flux excess. As the cloud of SN ejecta expands, it collides with the companion. This impact shocks the expanding material, creating a hole in the otherwise optically thick ejecta shell through which radiation can escape. An excess flux is produced in the shocked gas, propagating in the direction of the observer, and it should be detectable when the geometry is favorable and the observer looks into the companion star. As the equilibrium temperature of the shocked debris is inversely proportional to the distance from the WD center to the power of 3/4 (see Equation (7) in K10), the flux excess is larger the larger the separation from the companion is, and assuming Roche lobe overflow, RG companions will leave the most prominent signature. The intensity of the feature is higher in bluer bands (see Section 3). The effect only lasts a few days, completely vanishing by 10 days after the explosion.

With detailed early-time light curves we may be able to identify the progenitor system of a particular SN explosion, singling out events generated by red giant progenitors when seen from favorable angles. Unfortunately, early detailed SN light curves, with daily or so cadence, are still rare. New surveys such as the PanSTARRS Medium Deep Survey (PS1; Pastorello et al. 2010) and the Palomar Transient Factory (PTF; Law et al. 2009) provide well-sampled early SN Ia light curves, which might lead to the identification of progenitors in individual cases, as might early UV follow-up.

With the large collection of light curves provided by surveys such as the Supernova Legacy Survey (SNLS; Astier et al. 2006) and the Sloan Digital Sky Survey (SDSS; Abazajian et al. 2009), the companion scenarios can be constrained in a statistical fashion. The SDSS collaboration recently searched for evidence of an early flux excess due to shocking in high signal-to-noise ratio (S/N) spectroscopically confirmed SN Ia light curves from the SDSS-II survey. Finding no evidence of shocking-related excess in a subset of 108 confirmed SNe Ia with well-observed early-time behavior, Hayden et al. (2010a) conclude that RGs cannot be the main channel for SN Ia explosions. Here we use confirmed SNe Ia from the first three years of SNLS data to set an upper limit to the contribution of RGs to SN Ia progenitors.

After describing the data set used here, consisting of spectroscopically confirmed SNe Ia from the first three years of SNLS, and the processes used to standardize the data and generate composite light curves (Section 2), in Section 3 we summarize the results presented in K10 and show our rendering of these models. We then describe the statistical tests that allowed us to derive constraints to the contribution from RG progenitors to SN Ia explosions (Section 4). We also extended our analysis beyond the spectroscopically confirmed sample to include photometrically selected SN Ia light curves, showing that light curves affected by shock were not rejected as SN Ia spectroscopic follow-up candidates in SNLS because of a selection bias, and that our conclusions extend to the photometrically selected SNe Ia (Section 5). Finally, in Section 7 we summarize our results and outline future work.

2. SNLS DATA, THIRD YEAR

The data set used here is described in detail by Conley et al. (2011), Guy et al. (2010), González-Gaitán et al. (2011), and Bazin et al. (2011). We use data from the first three years of the SNLS. The SNLS is a rolling survey that gathered photometric data at the Canada–France–Hawaii Telescope (CFHT). Two independent photometric pipelines, based in France and Canada, are used for the SNLS data reduction (Bazin et al. 2011; Perrett et al. 2010). Here we use the photometry output of the French pipeline. SNLS light curves, originally collected in griz (Regnault et al. 2009b), are k-corrected (Hsiao et al. 2007), and standardized by applying a stretch factor, to broaden or narrow the rest-frame timescale of the light curve (Perlmutter et al. 1997), in order to generate rest-frame B- and V-band light curves.16 We define the variable τ as

$$\tau = \frac{t - t_{\text{max}}}{s(1 + z)}, \quad (1)$$

where \(t_{\text{max}}\) is the date of maximum flux (in the rest-frame B filter band), \(z\) is the SN redshift and \(s\) is the stretch; \(\tau\) represents the rest-frame, stretch-corrected, time to peak B luminosity. We processed the light curves using the SIFTO method (Conley et al. 2008) and we used a single template to fit the data and stretch correct the light curves. In processing the SN data, we assumed a rise time \(\tau_r = 17.4\) days, the time elapsed between explosion and maximum B luminosity, according to what González-Gaitán et al. (2011) find in a similar (but larger) SNLS data set, and it is also consistent with the rise time derived by Hayden et al. (2010b) from SDSS-II SNe Ia (\(\tau_r = 17.38 \pm 0.17\) days).

Our primary analysis is focused on spectroscopically confirmed SNe Ia. The first three years of SNLS data offer over 200 spectroscopically confirmed SNe Ia light curves. The original data set was reduced to 87 SN light curves by applying quality and redshift cuts described below. The final data set uses only SNe that satisfy the following requirements.

1. They are spectroscopically confirmed Type Ia SNe at redshift \(z < 0.7\) (135 light curves).
2. The total reduced \(\chi^2\) for the SIFTO template fit, applied to epochs \(\tau > -10\) days, is better than 3.0 (130 light curves).
3. The error in the determination of the peak date is \(\Delta t_{\text{max}} < 0.7\) days (117 light curves).
4. They have at least three data points in rest-frame B and three data points in the rest-frame V band in the rise portion of the light curve, \(-10 \leq \tau \leq 0\) days, to ensure the quality of the pre-peak fit (87 light curves).

The excess due to shocking may be visible up to 10 days after explosion (K10), or \(\tau = -8\) given our choice of \(\tau_r = 17.4\) days. No data prior to \(\tau = -10\) days were used to standardize the data and generate our composite light curves in order to avoid including in the light-curve fitting process data points potentially

16 Note that this is different from what is done in the processing of SN Ia light curves for cosmology, where the stretch correction is applied to the rest-frame template to match the data (Conley et al. 2011; Sullivan et al. 2011).
affected by the excess that we are seeking. Different choices of minimum day (between -10 and -7) were also tested and they do not affect our result. However, removing points earlier than \( \tau = -8 \) causes, in a few cases, a poor light-curve fit, and thus a larger scatter in the data. Visual inspection reveals that none of those SNe Ia for which the fit parameters significantly change if data points between \( \tau = -7 \) and -10 are excluded is actually affected by shocking. Thus, we conclude that including points at \(-8 < \tau < -10\) only strengthens the significance of our results.

The templates adopted to process the data (Conley09c and Conley09f\(^{17}\); Conley et al. 2008) assume a parabolic behavior at times prior to \( \tau = -10 \) days,\(^ {18}\) as described in Goldhaber et al. (2001), Conley et al. (2008), and the references therein:

\[
f(t) = \alpha (\tau - \tau_r)^2.
\]

where \( f \) is the flux as a function of time \( t \) and rise time \( \tau_r \). This is consistent with a simple expanding fire ball modeling of the exploding ejecta (see for example Riess et al. 1999), with \( \alpha \) representing the rise "speed," which is what we expect in the absence of shocking by a companion. We refer the reader to González-Gaitán et al. (2011) for a detailed study of the rise behavior of SNe Ia in the SNLS data.

Hayden et al. (2010b) found that a better fit to the SDSS-II data can be achieved using two separate templates to fit the rise and fall portion of the light curves, thus obtaining two stretch values. While using two stretches slightly improves the \( \chi^2 \) per degree of freedom the individual light-curve fits, \( F \)-tests show that for these SNLS data the improvement achieved using two stretches is not significant (see also González-Gaitán et al. 2011). Furthermore, because we use only data points at \( \tau \geq -10 \), with the five-day cadence of the SNLS data, we generally have only two to three points in the rise portion of each light curve that would be used for fitting. Fitting separately the rise and fall portions of the light curve then exposes us to the risk of misfitting or overfitting the rise portion. We conclude that it is best to use a single stretch template for the purpose of this analysis.

A more detailed description of the standard SNLS light-curve processing can be found in Conley et al. (2006, 2011) and Guy et al. (2010). For a discussion on the SNLS photometric calibration, see Regnault et al. (2009a).

\(^{17}\)We see no difference in our results choosing either Conley09c or Conley09f, and where not specified we will refer to Conley09f throughout the paper.

\(^{18}\)In fact, the SiFTO method allows as well for a cubic fit to the early rise portion of the light curves, but this was found not to improve the light-curve fit in most cases (Conley et al. 2008).

The SNLS light curves, normalized to peak flux \( f_{\text{peak}} = 1 \) in each color channel, stretched, and \( k \)-corrected as described above, can be combined into a composite light curve: our composite rest-frame \( B \) (\( V \)) light curve contains a total of 1059 (1125) data points between \( \tau = -20 \) and \( \tau = 40 \), and 202 (217) in the 10 days after explosion that would be affected by the flux excess: \(-17.4 < \tau < -7.4 \) days. The composite \( B \) and \( V \) light curves are shown in Figure 1, with the \( B \)-band flux on the left-hand side and the \( V \)-band flux on the right-hand side.\(^ {19}\) The data points potentially affected by the shocking excess are plotted in red and included within vertical lines.

3. MODELS

After an explosion, the SN ejecta expands and collides with the companion star, if one exists. K10 showed that this impact shocks the SN ejecta, creating a hole in the expanding material. Radiation can now escape from the otherwise optically thick ejecta shell. An early X-ray emission, analogous to the X-ray flash in core-collapse SN (Soderberg et al. 2008; Modjaz et al. 2009), should last minutes to hours, with little chance to be observed. In UV and optical bands, the flux excess lasts longer: the gas begins expanding to refill the hole carved by the companion. Radiation continues to diffuse out of this hot, shocked region, and it is observable until the \( ^{56}\)Ni luminosity begins to dominate the light curve. The timescale for this process is roughly 5–10 days. The effect is more prominent in bluer bands and can span over an order of magnitude in flux in UV, generating an early peak even brighter than the peak luminosity in the absence of shocking, while it is substantially dimmed in the \( V \) band.

The size of the hole and of the shocked gas region, and thus the amount of radiation escaping, depend essentially on the solid angle subtended by the companion carving the hole, and on the velocity of the ejecta at the time of impact. The models assume that the companion star is in Roche lobe overflow and the geometry of the system (semimajor axis of the binary orbit and size of the Roche lobe) is set by the nature of the companion. This excess radiation is then a powerful tool for identifying the SN progenitor system.

K10 considered three types of companions: a \( 2 M_\odot \) MS star, at a distance \( a = 5 \times 10^{11} \) cm from the WD, a \( 6 M_\odot \) MS

\(^{19}\)For a discussion of the distinction between photon-based and energy-based flux, see Nugent et al. (2002). Throughout the paper, we refer to flux as photon-based flux.
Figure 2. K10 model for a WD accreting from an RG companion is shown. At the center is a schematic representation of the SD explosion scenario: in the expanding ejecta, gray, the impact with the companion star (black circle) has created a hole, here simplistically represented by a cone. To the left and right, according to the corresponding viewpoint, are the rise light curves for, respectively, an observer looking in the opposite direction from the companion (no excess), and looking into the companion and the hole created by the impact (maximum excess), for the case of a WD–RG progenitor system. The scatter in the model is simply due to statistical noise in the numerical simulations (see Section 3). The solid line is the Conley09f template.

Figure 3. Models of excess emission over a nominal—parabolic—SN light-curve template, in units of peak luminosity, signature of shocking by a companion star, for the cases considered in K10: an RG companion (red filled circles), a $6 M_\odot$ (blue empty circles), and a $2 M_\odot$ (green crosses) MS companion, all in Roche lobe overflow (separation from the core of the explosion $a = 5 \times 10^{11}$, $2 \times 10^{12}$, and $2 \times 10^{13}$ cm, respectively). The effect is shown averaged over all observing angles. SN Ia spectra are generated from K10’s simulations as described in Section 3.1, and filtered through standard $B$ and $V$ filters to generate the theoretical light curves. The error bars represent the scatter—standard deviation—in the models. The left plot shows the effect in the $B$ band and the right-hand plot in the $V$ band. (A color version of this figure is available in the online journal.)

The models are generated from two-dimensional Monte Carlo radiation transport simulations that are subject to random sampling errors. Such errors are purely statistical, and do not take into account any of the possible systematic errors or uncertainties in the model calculations. The statistical errors are accounted for throughout our analysis.

The excess generated by shocking is shown in Figure 3, averaged over viewing angles, for all three progenitor scenarios in both the $B$ and $V$ bands. It is evident that, while the RG progenitors generate a significant excess, and a very distinct effect in both $B$ and $V$ bands, the time behavior for MS stars is only marginally changed in the presence of shocking, especially after averaging over viewing angles. Such a small deviation from the parabolic early rise behavior would hardly be detectable in the presence of the typical noise of SNLS data.
Therefore, we restrict ourselves to the RG scenario and only try to constrain the RG contribution to SN progenitor systems. We also expect that the explosion in a DD scenario would show even smaller, or no, deviations from a parabolic behavior. We thus tentatively associate the DD scenario with the standard template. Note, however, that it is possible, as mentioned in K10 and shown in Fryer et al. (2010), that in a WD merger, gas would be blown out to large radii ($\sim 10^{13}$ cm), producing a shock signature, with a UV excess possibly propagating through visible wavelengths. However, the simulations in Fryer et al. (2010) generally produce light curves rather dissimilar from standard SNe Ia, with a broader visible band light curve, unlikely to match SNe Ia in our sample.

Where needed, we will assume that any explosion not generated by an RG–WD binary pair has equal probability of arising from any of the three remaining scenarios.

### 3.1. Rendering of the Models

The K10 simulations generate full spectra of the SN explosion, including the effects of shocking, at time intervals of 0.1 days for the first 10 days after explosion. The spectra are integrated on a day timescale and filtered through the same $V$ and $B$ filters into which the SNLS data have been converted. This is done for every angular separation between the WD and the companion, in 40 equal intervals of observing probability, for the three progenitor scenarios considered: RG, 6 $M_\odot$, and 2 $M_\odot$ MS sub-giants.

The K10 spectra are designed to reproduce the excess generated by shocking on top of a nominal template. The input template in the models is irrelevant to the shocking physics. We use the spectra for the smallest companion scenario ($M = 2 M_\odot$) at the largest angular separation ($\sim 180^\circ$), where we expect the effects of shocking to be entirely negligible, as in a neutral template: a template with the absence of shocking. To better reproduce what we actually expect the result of shocking to look like in an SNLS light curve, we subtract the neutral template from the light curve templates generated as described above. The new light curves are shown in Figure 3, averaged over all angles, and they describe the excess due to shocking. This excess can be added to the parabolic portion of the templates to reproduce what we would expect to see in our data. Recall that this portion of the light curve is not used to standardize the SNLS data and generate the composite light curves.

We now have template light curves for the first 10 days of an SN Ia explosion in the SD scenario, with different companion stars and at different observing angles, which can be compared to the SNLS observations.

### 4. Tests

#### 4.1. Template Goodness of Fit

We begin by noticing that the fit of the composite SN to the SN template (here Conley09c and Conley09f were used, with no significant differences) is worst in the region of interest for the shocking effect, $\tau < -7$ days to peak, in both $B$ and $V$ bands.

Figure 4 shows the median, binned by day, of the composite light curves (top plots). The error bars represent the scatter—standard deviation—of the individual measurements (the standard deviation is measured as conventionally done with respect to the mean and we ignore the error of each measurement). The bottom plots show the deviation from the template as the difference between the data, $f$, and in the template, $T$, at time $t$, over the error in the data $\sigma(t)$, averaged over each day:

$$\sum_{t \in \text{ day}} \frac{f(t) - T(t)}{\sigma(t)},$$

as an estimator of the goodness of fit of the template to the composite light curve. The propagation of errors along the time dimension is also ignored.

The most significant deviation from the template happens in both $B$ and $V$ bands roughly prior to $\tau = -10$ days, with a clear excess in the $B$ band at $\tau \lesssim -12$ or in the first few days after explosion. It is intriguing that the deviation is more prominent in the $B$ band than in the $V$ band, consistent with the chromatically biased effect that shocking by a companion would produce. Note, however, that this is the portion of the light curve that is
not fit to the template, and it is thus not surprising to see a larger scatter here.

4.2. Simulations

Having found a deviation from our fiducial SN Ia template in the early days after explosion, we test if this can be attributed to shocking by a companion.

With the K10 templates in hand, we can create synthetic SN Ia rise light curves that incorporate the effect of shocking for the different progenitor scenarios, as seen from different viewing angles. We start off with the standard parabolic rise templates (Conley09f). In each band, we add the excess described by the models (Figure 3) to our standard template. For each epoch corresponding to the SNLS data, we draw a data point from the new template thus obtained. To choose the viewing angle from which this data point should come we draw angles with equal probability between 0° and 180°.

Families of synthetic light curves are generated using increasing contributions of data points from the RG progenitor scenario, and drawing the remaining points equally likely from a parabolic template (DD scenario), the 2 $M_\odot$, and the 6 $M_\odot$ MS progenitor scenarios. We generate families with 0% RG contribution, to 100% RG contribution, in steps of 10%. A finer grid was also tested, but a resolution of 10% in the RG contribution is adequate to represent the progenitor populations given our errors.

In our test, we have to account for the errors in both the templates and the data. Thus, at a given epoch, in generating the simulated data points, we draw each flux value from a Gaussian distribution around the template value at the corresponding epoch, with the width of the Gaussian is the sum in quadrature of the errors in the SNLS data and in the model.

For each RGfrac between RGfrac = 0% and 100%, we create 100 sets of simulated observations, in steps of 10%, thus generating 100 synthetic light curves per RGfrac, each one the size of the rise portion of the light curve: 202 points in the $B$ band and 217 in the $V$ band.

4.3. One Band K-S Test

We then compare each population of synthetic light curves to our composite light curves. We chose the non-parametric two-sample Kolmogorov–Smirnov (K-S) test (Peacock 1983) to do so. This simple statistical test measures the maximum distance between the simulated and true cumulative light curves, and we find it is a sensible statistic to determine the presence of an excess in data with large scatter. The K-S tests are nonparametric, and thus do not require us to make any assumptions on the distribution of data, and, unlike, for example, the Pearson’s $\chi^2$ statistics (Rice 2001), do not require binning the data. The SNLS data points are sorted by flux, and added to generate a cumulative flux distribution. Similarly, a cumulative flux distribution is generated for each synthetic realization. The maximum distance between two cumulative distributions is a measure of the level at which the null hypothesis that the data sets being compared come from the same distribution can be rejected (see Figure 5).

In other words, comparing the true data with synthetic data generated from scenarios with different RG contributions, we test if the data come from a distribution with a given fraction of RG progenitors, RGfrac.

For each RGfrac, we pair each of the 100 sets of simulated observations with our true light curve, apply a two-sample K-S test, and average over the 100 K-S numbers. This allows us to obtain the confidence level for the rejection of the null hypothesis—that the two sets being compared came from the same distribution—and its statistical errors, accounting for all sources of noise: the uncertainty in the models, in the data, and for the presumed diversity in SN Ia progenitors.

Using only the $B$ data, and within 1σ error bars, we reject at roughly 90% confidence level (c.l.) the hypothesis that a progenitor population with RGfrac $\gtrsim$ 30% has generated our data. A contribution of more than 40% is ruled out at the $>95%$ c.l. These results are largely consistent with the analysis presented in Hayden et al. (2010a), and with the upper limits placed by Gilfanov & Bogdán (2010) on SN Ia in elliptical galaxies. Accounting for all angles, with only $\sim$200 data points in the 10 days that would be affected by the shocking effect, we would expect <40 data points to be affected significantly by the effect we are probing, even if all companions were RGs. This is therefore a small number statistics problem, in the presence of noise in both data and models, and it is not surprising that we have a limited ability to place strict limits on the contribution of RG progenitors this way. However, we will obtain stronger limits by including considerations on the color bias in the shocking excess in Section 4.4.

Noticeably, despite the noise, the probability that the true and synthetic distributions of data points come from the same progenitor distribution clearly decreases monotonically as we increase the contribution of RG systems, particularly in the $B$ band (Figure 6). This strongly suggests a minimal contribution of RGs to SN Ia progenitors. Similarly, an almost monotonic decrease in probability (increase in c.l.) is evident in the $V$ band, though less pronounced. This is expected, on account of a smaller signature of shocking in redder bands (see Figure 2).

4.4. K-S Chromatic Test

In this section, we investigate the chromatic bias in the shocking footprint. In the absence of shocking, the expected time behavior of the SN explosion is a parabola, similar in the $V$ and $B$ bands. Thus, in the rise portion of the light curves, we would expect points drawn from a set of SNe to come, statistically speaking, from the same distribution in the $V$ and $B$ bands. However, in the K10 simulations (see Section 3), the $V$ and $B$ time behavior differ dramatically in the rise portion of the light curve in the presence of RG progenitors. We again
perform a two-sample K-S test. This time we want to assess the similarity of the $B$ and $V$ populations of early-rise data, so for the SNLS data, we compare the $B$ and $V$ channels with a K-S test, and we do the same for each synthetic population.

We find that the hypothesis that rest-frame $B$ and $V$ populations of data points from the composite true SNLS light curves, days 0–10 after the explosion, come statistically from the same distribution can only be rejected to 5% c.l., or equivalently that the hypothesis that the two channels come from the same distribution has a $p$-value of $\sim 0.95$.

We compare the synthetic $B$ and $V$ light curves and find, as expected, that the K-S number increases with the increasing RG contribution: the probability that the $B$ and $V$ synthetic data come from the same distribution decreases as more RG progenitors are used in the progenitor mix.

The results of this test are plotted in Figure 7. Within 1σ error bars, only the population with no contribution from RG progenitors is consistent with the SNLS data. We rule out a contribution $RG_{frac} \gtrsim 10\%$ at $\sim 2\sigma$, and greater than 20% at the $>3\sigma$ level.

### 4.5. Color Distributions

In standardizing our light curves we have chosen one stretch value for each light curve to be applied to all rest-frame bands. We ask the question: could there be a correlation between $V$ and $B$ that would interfere with the result of our K-S chromatic test (see Section 4.4). Suppose some data points in the region $\tau < -10$ days, which is not fit to the template, have more (or less) flux than the template, so that if we included those points when fitting the light curve to the template, we would have generated different fit parameters, and a different value for the stretch or day of maximum; in this case, both the $B$ and $V$ light curves would show flux in excess (deficit) of the template in the shock region. We might then see a correlation in our chromatic K-S test beyond this possible systematic effect. We test the color of our true and simulated light curves by taking $f_{B-V}$ to be the difference of the $B$ and $V$ fluxes after normalizing each channel at peak. Under the assumption that in the absence of shocking the rise portion of the light curve would follow a parabolic behavior identical in both bands, diverging only at $\tau \gtrsim -9$ as modeled in the Conley09f template, the distribution of $f_{B-V}$ values should be consistent with zero for our composite light curves, while the effect of shocking would produce a distribution of $f_{B-V}$ with a positive mean, and a large standard deviation.

For every flux point in each normalized, standardized rest-frame $B$ light curve, we subtract the flux of the closest rest-frame $V$ data point, within $\Delta \tau < 0.2$ days. Similarly, we generated synthetic colors for different RG fractions, by creating pairs of $V$ and $B$ synthetic light curves, accounting as usual for the typical error bars in the data and in the models. We derive the distribution of colors for both true and simulated data.
The $f_{B-V}$ distributions are plotted in Figure 8. The top panel shows the $f_{B-V}$ distribution for true data. There is no blue excess in flux in the true color; in fact, the distribution has a mean of $\mu \sim -8 \times 10^{-4}$, a median $\sim 0.002$, and a standard deviation $\sigma \sim 0.054$: statistically consistent with a random distribution around zero.

The distributions generated from simulated light curves are shown below the distribution for true data in Figure 8, for RG contributions $\text{RG}_{\text{frac}} = 0\%, 33\%, 66\%$, and $99\%$, plotted from the top to the bottom. Each distribution is generated from a factor of 100 more points than the true color distribution and is thus minimally noisy. The mean of the distribution increases as we increase $\text{RG}_{\text{frac}}$ and the distributions get increasingly asymmetric, weighted toward positive values of $f_{B-V}$ (bluer color). The synthetic distributions generated with no RGs ($\text{RG}_{\text{frac}} = 0\%$) have moments that are extremely similar to those of the true color distribution: $\mu \sim 2 \times 10^{-3}$, median $\sim 0.001$, and $\sigma \sim 0.077$. Once again, this shows that the distribution of colors in the SNLS data is compatible with minimal—or no—contribution of RG to SN Ia progenitors, confirming the results obtained from the K-S tests.

5. PHOTOMETRICALLY SELECTED SNe Ia

The excess due to shocking of the SN ejecta affects the early time domain photometric and spectral behavior of the SN Ia explosions. Since in surveys such as SNLS and SDSS, SN Ia are identified by their early light curves, and thus an explosion is followed up spectroscopically only if it is thought to be an SN explosion, an interesting question is whether this early effect might have led to the rejection of phenomena that indeed were SN Ia, but deviated from the expected early behavior on account of shocking. In Hayden et al. (2010a), a subset of unconfirmed SN Ia is visually inspected and no such effect is found. We investigate 905 SNLS light curves with some redshift information, either spectroscopic or photometric. We exclude likely or known active galactic nuclei, variable stars, and core-collapse (CC) SNe. In order to avoid contamination from unidentified SNe II, Ib, or Ic, we also apply cuts in stretch and color space. In particular, CC SNe show a different average color than SNe Ia, and color constraints eliminate them from the sample. A detailed discussion of photometric selection of SNe Ia in the SNLS data can be found in Bazin et al. (2011). We thus believe that our new data set has minimal contamination from non-SN Ia events. Our new data set contains 336 light curves before our cuts are applied (see Section 2), and 110 thereafter. Our new composite light curves contain 251 points in the rest-frame $B$ and 270 in the rest-frame $V$ in the region of interest: $\tau = -17.4$ to $-7.4$ days to peak (Figure 9).

We repeat the K-S tests applied earlier to the extended SN Ia set and find that the statistics confirm the upper limits set to the contribution of RG binary systems to SN Ia explosions (Figures 10 and 11). The K-S test of the composite light curve in each $B$ and $V$ with the respective synthetic light curves is entirely consistent with the test for the spectroscopically confirmed SN Ia subset, and consistent with minimal or no contribution of RG to the SN Ia progenitors.

6. U-BAND DATA

As described in Section 3, the excess due to shocking is more prominent at bluer wavelengths. In the $U$ band, the models of K10 predict an excess over a nominal template more pronounced by roughly 20% over the $B$ band for the RG case, averaged over all angles and over the first 10 days after explosion. The prediction for the angle-averaged excess in the $U$ band is shown in Figure 12. We thus extend our analysis to the rest-frame $U$ band data, to see if a stronger constraint can be placed on the contribution of an RG to the SN Ia progenitor population. Three years of SNLS spectroscopically confirmed light curves are processed as described in Section 2 in order to generate rest-frame $U$-band light curves. The light curves are then selected if they pass similar cuts to those described earlier.
1. They are spectroscopically confirmed Type Ia SNe at redshift $z < 0.7$ (135 light curves).
2. The total reduced $\chi^2$ for the SiFTO template fit, applied to epochs $\tau > -10$ days, is better than 3.0 (130 light curves).
3. The error in the determination of the peak date is $\Delta d_{\text{max}} < 0.7$ days (117 light curves).
4. They have at least three data points in the rest-frame $B$, three data points in the rest-frame $V$, and three in the rest-frame $U$ band in the rise portion of the light curve, $-10 \leq \tau \leq 0$ days, to ensure the quality of the pre-peak fit (57 light curves).

The rest-frame $U$ band composite light curve thus generated is plotted in Figure 13, and it contains 662 points between days $-20$ and $40$ from explosion, and 123 in the region of interest: $-17.4 \leq \tau \leq -7.4$. Applying the latter cut, which is more restrictive than the corresponding cut in our primary analysis, the new composite $B$ and $V$ light curves contain, respectively, 152 and 161 data points in the region $-17.4 \leq \tau \leq -7.4$. It is immediately evident that the $U$-band composite light curve is significantly noisier than the $B$ and $V$ composites, and it contains
Figure 13. Composite $U$ light curve from three years of SNLS data. Symbols are as described in Figure 1. (A color version of this figure is available in the online journal.)

Figure 14. Results from two-dimensional K-S applied to the early rise portion of the composite $U$ (black crosses), $B$ (blue full circles), and $V$ (red empty circles) light curves; 1σ error bars are shown. This figure reproduces Figure 6 in the three color bands, and for the subset of light curves selected by the cuts described in Section 6. In the $U$ band, an RG fraction of 30% and its 3σ error bars lie below the solid line, which indicates the 0.95 c.l. of rejection of the hypothesis that the simulated and true data come from the same distribution. (A color version of this figure is available in the online journal.)

We generate synthetic $U$-band light curves as described in Section 4.2 and we reproduce the two-sample, monochromatic K-S test described in Section 4.3 for the $U$-band data. We find that the true data distribution once again grows dissimilar from the simulated distribution as more RG progenitors are included in the simulation (Figure 14). Using the $U$ data, a progenitor fraction $\text{RGfrac} > 30\%$ is ruled out at the 3σ level. The results of the single band K-S test for the $B$ and $V$ for the subsample of light curves that pass the new set of cuts are also plotted, and they are entirely consistent with the results obtained in Section 4.3, though with larger errors on account of the smaller data set size.

Note that the $U$-band data, even in the absence of RGs in the simulated data, appear from a K-S test to be different at the 2σ level from the parabolic-rise model (i.e., the 2σ limit of the c.l. of rejection of the null hypothesis that synthetic and true data come from the same distribution is below c.l. = 0.1).

Figure 15. $f_{U-V}$ (left column) and $f_{U-B}$ (right column) distributions for true (top) and simulated data (four bottom plots) with different contribution of RG progenitors. The mean and standard deviation of each population are indicated by arrows. This figure reproduces Figure 8 for the $f_{U-V}$ and $f_{U-B}$ colors.

As in all other cases considered, the distribution of simulated color becomes increasingly different from the distribution of true data as we increase the contribution of RG in the progenitor mix for our simulations.

35% fewer light curves, and roughly 40% fewer relevant data points.

We generate synthetic $U$-band light curves as described in Section 4.2 and we reproduce the two-sample, monochromatic K-S test described in Section 4.3 for the $U$-band data. We find that the true data distribution once again grows dissimilar from the simulated distribution as more RG progenitors are included in the simulation (Figure 14). Using the $U$ data, a progenitor fraction $\text{RGfrac} > 30\%$ is ruled out at the 3σ level. The results of the single band K-S test for the $B$ and $V$ for the subsample of light curves that pass the new set of cuts are also plotted, and they are entirely consistent with the results obtained in Section 4.3, though with larger errors on account of the smaller data set size.

Note that the $U$-band data, even in the absence of RGs in the simulated data, appear from a K-S test to be different at the 2σ level from the parabolic-rise model (i.e., the 2σ limit of the c.l. of rejection of the null hypothesis that synthetic and true data come from the same distribution is below c.l. = 0 for all synthesized populations). The simulated light curves are generated as described in Section 4.2, and an adiabatic (parabolic) expansion is postulated up to six days after the explosion. However, effects of line opacity and dispersion in the spectra at wavelengths bluer than $\lambda = 400$ nm, as described in Ellis et al. (2008), affect the $U$ light curve, and may modify it from our simple model prediction. This can explain the relative low correlation between our true and simulated data, which is revealed by the K-S test. For this reason, we are reluctant to apply the chromatic K-S test described in Section 4.5 to the $U$-band data, as our assumption that the $U$ and $B$, or $U$ and $V$ light curves would have identical early rise behavior might not hold here. As a tool to aid visualization though, in Figure 15 we reproduce Figure 8 for the $f_{U-V}$ and $f_{U-B}$ data (Section 4.5). As in all other cases considered, the distribution of simulated color becomes increasingly different from the distribution of true data as we increase the contribution of RG in the progenitor mix for our simulations.
We limit ourselves to pointing out that the $U$-band data confirm the constraints that we set with $B$ and $V$ data.

7. CONCLUSIONS

We analyzed three years of spectroscopically confirmed SNe Ia from the SNLS survey, looking for an early rise flux excess that could be attributed to shocking by a companion. We created a composite light curve standardizing the data with the SiFTO method, excluding from the fit the region that might be affected by the shocking phenomenon.

We found a worsening of the fit of the data to the standard templates in the first few days after the explosion (Section 4.1), but we found no evidence that is due to anything but the fact that the data prior to $\tau = -10$ are not used in the template fit.

We used the spectra generated by the K10 (Kasen 2010) simulations to model the expected SN Ia time domain behavior in the SD scenario, thus we can account for sources of noise in the models, as well as in the data. We found no evidence of flux excess in our data, and conclude that, based on the K10 models, the contribution from RG progenitors is less than 10% in the SNLS three-year sample. We thus set a $\sim 2\sigma$ upper limit of 10% on the contribution of RG–WD binary systems to the SN Ia progenitors, and a $\sim 3\sigma$ upper limit of 20%. With roughly 100 light curves in our sample, with a contribution of $\sim 10$% light curves from RG progenitors, $\sim 3$ data points could be affected by shocking. We cannot exclude such a small contribution from RG binary systems in the presence of noise from both the models and the data. Our results are robust when tested in a photometrically selected sample of light curves, as well as using the $U$ band data.

Our conclusion agrees with the results derived by Hayden et al. (2010a) from the SDSS-II SN Ia sample. Our analysis differs, other than in the SN sample used, in the treatment of the shocking signature: while Hayden et al. (2010a) model the shocking as a Gaussian excess, we used the K10 simulation directly to characterize effects of shocking, thus including the uncertainties in the models. Furthermore, our analysis exploited the color bias in the shocking excess to set stronger constraints on the presence of shocking and are able to quantify the maximum allowed contribution of RGs to the SN Ia progenitors.

Although Bayesian tests (expectation minimization and Gibbs sampling) were applied to our data, the presence of noise, and the relatively high dimensionality of the problem, with four possible progenitor scenarios, does not allow us to firmly assess what contribution of RGs best reproduces the residuals we see in the data with respect to the parabolic templates. Our data are entirely consistent with no RG progenitors.

According to population synthesis studies, such as Ruiter et al. (2009), the SD scenario is expected to produce SN Ia mainly from evolved companions, i.e., they favor the RG–WD channel over the MS–WD channel, at least under the Roche lobe overflow requirement. In Ruiter et al. (2009), where reaching the Chandrasekhar limit is required, as it is assumed in this paper and in the K10 simulations, MS–WD binaries are responsible only for 5%–10% of the SN Ia production, while the majority of SNe Ia come from a system with an evolved donor: a sub-giant or giant. Limiting the contribution of RG–WD SN Ia progenitors from an observational point of view may then have a significant impact on the conclusions derived from population synthesis studies on delay time distributions and SN Ia progenitors.

PS1 (Pastorello et al. 2010) and PTF (Law et al. 2009) have begun providing well-sampled rise light curves, where the excess due to shocking by an RG progenitor, should this be a valuable channel to produce SN Ia, could soon be observed. Since the effect is predicted to be chromatically biased (see Section 3), PS1 is particularly suitable, offering data in SDSS $g$ and $r$ bands, thus allowing a color comparison. Early UV follow-up surveys (Cooke et al. 2011) are also a promising way to spot WD–RG progenitor systems, since the progenitor excess is extremely prominent in UV bands, provided that the follow-up can be triggered early enough after the explosion. SNLS continued collecting SN Ia time series through 2006, and as all SNLS data become available, more stringent limits may be set. Note that in the absence of any excess, the population of progenitors could be pinpointed to small ($M < 6 M_\odot$) progenitor companions. However, in the presence of detections of small excess signals, there would be a degeneracy between RG progenitors observed at some angular offset from the line of sight to the hole generated by the companion, and more massive MS companions, and a large sample is indeed necessary to disentangle these two scenarios. Possibly, only a survey as large as LSST (LSST Science Collaboration 2009) would offer the opportunity to assess the frequency of progenitor companion types in SNe Ia.

We also point out that the constraints derived here rely on the theoretical models described in K10. The shocking signatures predicted in K10 assume that the companion is in Roche lobe overflow, with the separation distance, $a$, only a few times the stellar radius, $R$. While this is expected in a typical accretion scenario, if $a \gg R$, the solid angle subtended by the companion would be smaller, and so would be the effect of shocking. Justham (2011), for example, argues that the donor star in the SD scenario might shrink rapidly before explosion, having exhausted its envelope; the companion star would then be many times smaller than its Roche lobe, reducing the shocking signature, and also explaining the lack of hydrogen in spectra of SNe Ia. We look forward to more detailed theoretical work, which may relax the Roche lobe overflow assumption, integrate three-dimensional explosion models, and take into account possible absorption mechanisms within the systems, and the effects of the orbital motion, to better characterize the shocking behavior and its diversity.

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