PROCEEDINGS OF SCIENCE

Discovery of short-lived SN Ia progenitors

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We use the VESPA algorithm and spectra from the Sloan Digital Sky Survey to investigate the star formation history of the host galaxies of 257 Type Ia supernovae. We find 5σ evidence for a short-lived population of progenitors with lifetimes of 74 Myr or less. As standardizeable candles, Type Ia supernovae play an important role in determining the expansion history of the Universe, but to be useful for future cosmological surveys, the peak luminosity needs to be free of uncorrected systematic effects at the level of 1-2%. Given that the relative number of short-lived progenitors is likely to increase with redshift, this could lead to a systematic bias in future supernovae surveys.

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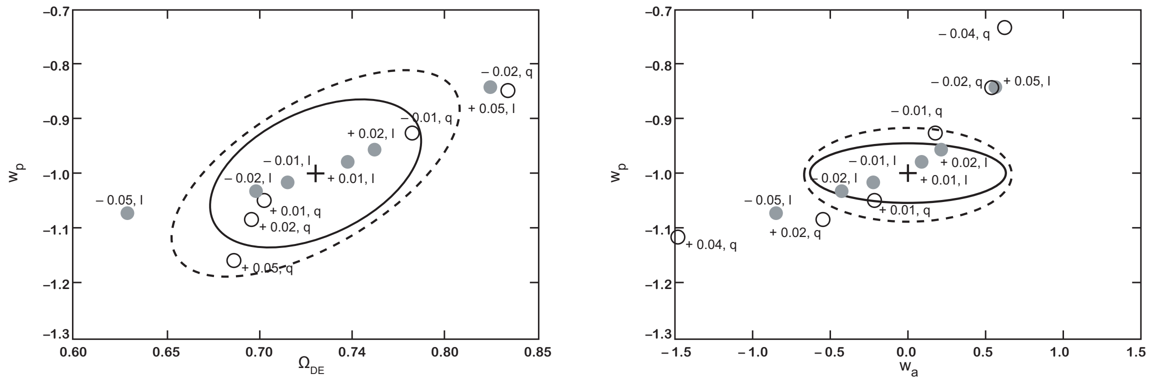

Figure 1: Effect of a SN luminosity bias correlated with redshift on the determination of the dark energy parameters Ω_E, w_p and w_a. The black ellipses are taken from the DETF report for a SNAP-like experiment. They correspond to the 95 % C.L. (left) or one-sigma (right) error for two hypotheses on the error budget: pessimistic (dashed line) or optimistic (solid line). We added the displacement in best fit value produced by a bias either linear (l, filled gray circles) or quadratic (q, open circles) in redshift. The quadratic bias peaks at $z = 1$. The value next to each dot is the magnitude difference at $z = 1$ (-0.05 to 0.05). Metallicity effects, for instance, are expected to behave like a quadratic bias with positive values [34, 26], and one can clearly see from this figure that they must be understood at the percent level not to dominate the measurement error budget.

1. Introduction

The relationship between peak brightness and redshift of Type Ia supernovae (SN Ia) depends on the cosmological model; this has provided the most direct evidence for the accelerated expansion of the Universe [29, 23]. Current SN Ia surveys such as SNLS [3], ESSENCE [38], and GOODS-SN [30] are contributing to current constraints on cosmological parameters, and SN Ia will continue to be important for cosmological constraints in the next generation of surveys such as the JDEM candidates ADEPT, DESTINY [4] and SNAP [2].

Type Ia supernovae are interpreted as the thermonuclear explosion of a white dwarf that has reached the Chandrasekhar mass and thus has become unstable, probably through accretion from a companion star (the single-degenerate scenario) or the merging with another white dwarf (the double-degenerate scenario). However, no fully consistent model of a SN Ia explosion has yet been built.

The natural scatter in SNe Ia peak luminosities covers roughly one magnitude; the rms peak luminosity is 0.45 mag after excluding outliers. Empirical correlations based on light curve shape [24] or intrinsic color [37, 36] allow reduction of the intrinsic scatter to about 0.13 mag, making them usable for cosmological measurements.

However, it is not yet known how much of the residual scatter is correlated with physical parameters that could evolve with redshift, and thus bias the measurement of cosmological parameters. Fig. 1 shows the bias in the dark energy parameters Ω_E, w_p and w_a caused by systematic errors in the calibration of peak luminosity with redshift. In order for SNe to be useful for constraining dark energy at the level expected in future SN satellite experiments, the evolution of luminosity at a given light-curve shape over the probed redshift range must be less than 1-2% [15].

There are several observational indications for a variety of delay times between the birth of the progenitor system and the explosion of the SN Ia, leading some authors to envision the existence of at least two different populations of SN Ia populating slightly different regions of stretch-brightness parameter space [33]. It is not yet known if they are described (at the percent level) by the same Phillips relation. If they are not, then this represents a source of scatter in the SN Ia Hubble diagram that in principle could be removed with measurements of the delay times. If the Phillips relations are different and the relative numbers of SNe in the two populations evolve with redshift, the values of cosmological parameters derived from the Hubble relation will be biased if we cannot determine population-dependent corrections.

The brightest supernova events only occur in actively star-forming galaxies ([10 – 12]), suggesting prompt explosions, while under-luminous events are most often found in spirals and E/S0 galaxies, whose old stellar populations would suggest delayed explosions [14]. Mannucci et al. ([18]) have proposed a two-component model for SNe Ia, and several authors [33, 19, 31] have shown that the supernova rate can be expressed as a sum of a term proportional to the total mass of the galaxy and a term proportional to the recent star formation rate. In the Mannucci et al. model, some of the supernovae would explode several Gyr after the birth of the progenitor system, while others after a fraction of a Gyr. Moreover, those two populations have different luminosities, the "prompt" component being brighter with broader light-curves [33]. The prompt component will dominate at higher redshifts when the Universe's age (or the time since star formation began) was less than the lifetime of the longer-lived progenitors. Determining the relative numbers of supernovae in the two populations is the first step in understanding any possible bias these populations might cause. Given the 13% scatter in the calibrated peak luminosities of supernovae, measuring systematic effects in the Phillips relation at the percent level will take samples of several hundred supernovae.

Hamuy et al. ([13]) used 62 SN Ia host galaxies to study the impact of host morphology, magnitude and colors on the decline rate Δm_{15}, which allows one to estimate the SN peak luminosity. They first claimed to find a correlation with both age and metallicity. In an erratum to that paper, they found that the metallicity dependence disappeared after they corrected the metallicity of three of their galaxies. However, their sample was very small and most of their estimates of age and metallicity were based on photometry only, without spectra of the host galaxies, and therefore their accuracy was limited. Moreover, although they investigated various environmental effects, their methodology was not sensitive to a second parameter in the Phillips relation, since they used the decline rate as a "reddening-free and distance-free estimate of the SN peak brightness", and thus assumed *a priori* the universality of the relation.

Gallagher et al. ([6]) carried out a similar analysis with spectra of 57 SN Ia hosts, and put tentative constraints on the SN progenitor lifetime using an estimate of current-to-average star formation rate. They claimed to see hints of both a bimodal behavior and a lower limit of the progenitor lifetime. They admitted that their findings were rather inconclusive.

Sullivan et al. ([33]) used 100 SNe from the SNLS and broadband spectral energy distributions of the host galaxies to estimate stellar masses and star formation rates. They found a component proportional to the stellar mass, and a component proportional to the recent star formation rate, averaged over the last 0.5 Gyr.

Our study improves on these earlier papers by using a larger sample of SNe, with spectra of their host galaxies from the Sloan Digital Sky Survey (SDSS; York et al. 2000). We use a sophisticated stellar population code called VESPA [35] which allows us to determine the stellar formation history of the hosts. We also determine the star formation history of a large sample of normal galaxies from the SDSS as a control.

2. Host galaxies and reference sample

We gathered a sample of about 1300 confirmed SNe Ia from IAU circulars[1], the CfA supernovae list[2] and the SDSS-SN public list of supernovae[3]. We cross-referenced this list with the SDSS DR5 [1] spectroscopic survey of galaxies: 256 galaxies with spectra were identified as SN Ia hosts, corresponding to 257 supernovae (one galaxy hosted two supernovae). The list of hosts used in this paper is available online[4].

The detection efficiency of this sample is unknown, as it depends in detail on the way in which the SN were found. To account for the selection function of SN Ia discovery, we also process a control sample of 10^5 DR5 galaxy spectra, weighted to reproduce the redshift distribution of the host sample — this is the parameter which could most significantly bias delay time measurements. Other effects will be discussed in section 4.

3. Reconstructing the star formation and metallicity history of SN host galaxies

The spectrum of a galaxy is a superposition of spectra of single stellar populations which formed at a given age with a given metallicity. Since it is not possible to recover the star formation and metallicity history with infinite precision [16], it is only sensible to attempt to recover the star formation and metallicity history with a certain time resolution. The VESPA algorithm [35] does this, providing a detailed history only where the data warrant it. Note that broad-band colors are not sufficient to determine the star formation histories of galaxies, as they suffer from significant age-metallicity degeneracies [16].

In brief, VESPA uses singular value decomposition to calculate the number of significant components in the spectrum of the galaxy. VESPA then uses an algorithm to determine the best-fitting non-negative values of the star formation fractions. Extensive tests of the performance of VESPA on synthetic spectra as a function of wavelength coverage and signal-to-noise ratio can be found in [35]. To limit the search to a manageable amount of parameters, and because currently available spectra never have the quality or spectral range to justify going beyond this choice, VESPA's finest resolution consists of 16 age bins, logarithmically spaced in lookback time between 0.002 and 14 Gyrs. Specifically, the lower limit in age of the 16 bins are: 0.002, 0.02, 0.03, 0.0462, 0.074, 0.115, 0.177, 0.275, 0.425, 0.6347, 1.02, 1.57, 2.44, 3.78, 5.84, and 9.04 Gyr. Below we will define the prompt SN population as that arising from the first four bins, i.e., within 0.074 Gyr, which corresponds to a main-sequence lifetime for a star of $\sim 5.5\ M_{\odot}$. The next bin (0.115 Gyr) corresponds to the main-sequence lifetime of a star of $\sim 3\ M_{\odot}$.

[1] `http://www.cfa.harvard.edu/iau/cbat.html`

[2] `http://cfa-www.harvard.edu/iau/lists/Supernovae.html`

[3] `http://sdssdp47.fnal.gov/sdsssn/sdsssn.html`

[4] `http://sn.aubourg.net/hosts/`

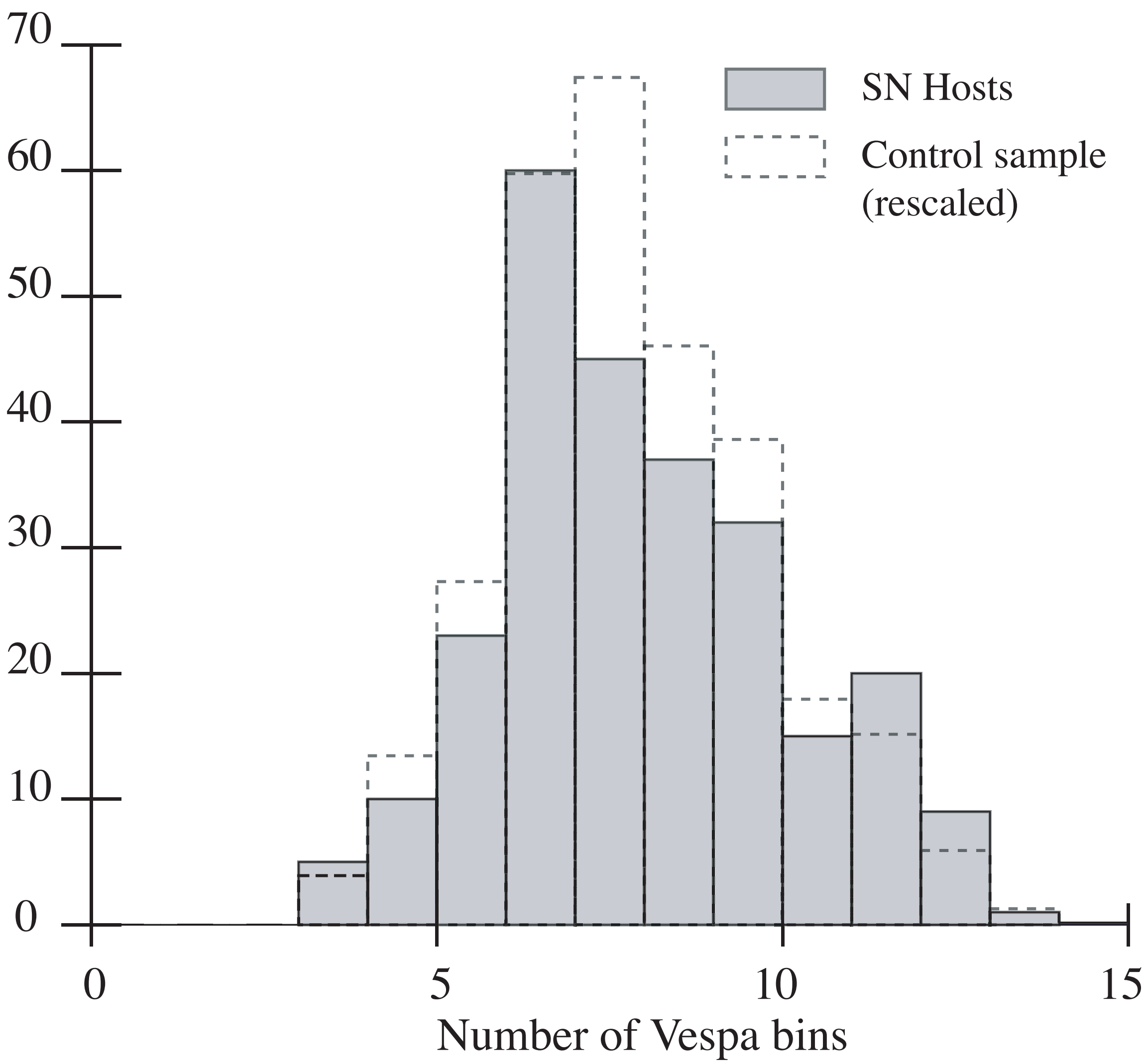

Figure 2: Distribution of the number of stellar populations recovered by VESPA from the host sample (white) and the control sample (gray). The two distributions are very similar.

VESPA chooses the number of stellar populations to model depending on the quality of the data. The SDSS galaxy spectra typically allow between 7 and 10 age bins in both the SN host sample and the control sample (Fig. 2; see also [35], although there is non-zero star formation in only 3-5 of those bins. The metallicity for each population is a free parameter, so there are as many metallicity values recovered as there are star formation fractions.

We estimate the number of supernovae per unit stellar mass as follows. If we assume that the supernova hosts are an otherwise unbiased sample from the SDSS, then the total supernova rate per unit stellar mass is proportional to the total number of supernovae divided by the total stellar mass in the SDSS control sample. The constant of proportionality is unknown, as it depends on the details of the SN selection. If, however, we assume that the supernova hosts otherwise represent an unbiased subset of SDSS galaxies, then we can adopt this procedure for any subset of the hosts and control sample, and the constant of proportionality will be the same. In this way we can obtain the

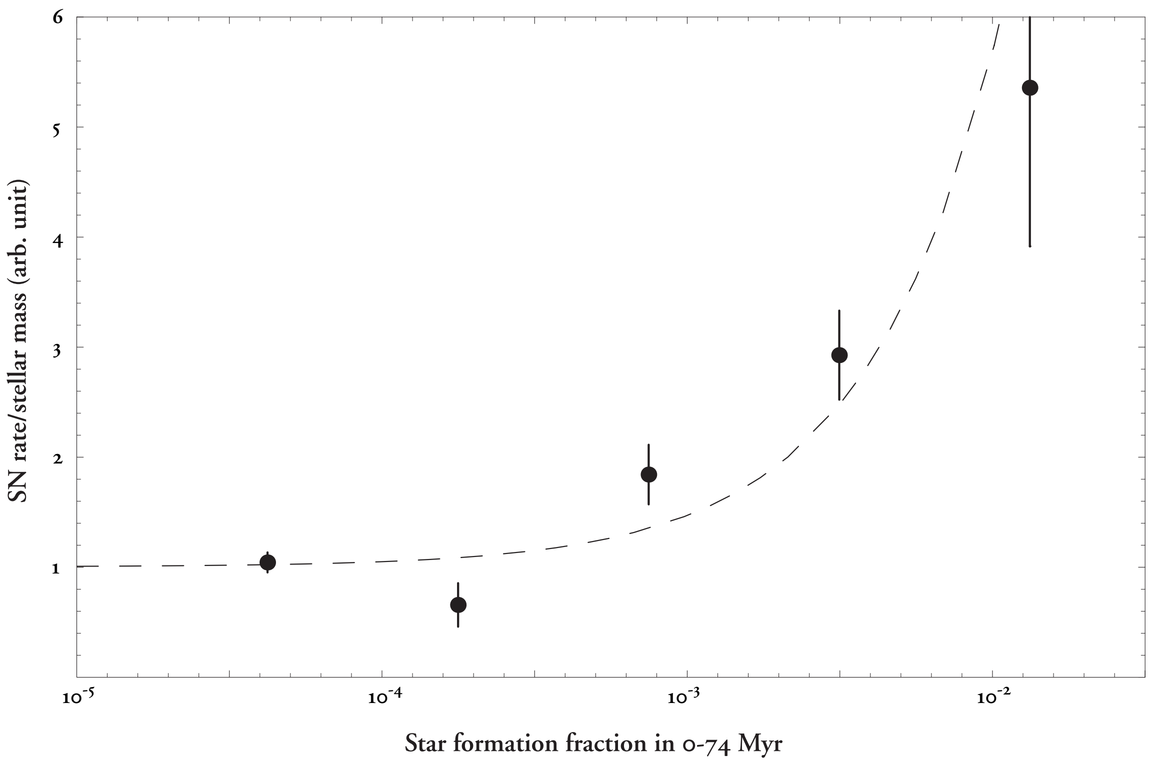

Figure 3: Type Ia supernova rate per stellar mass, unnormalized, vs. fraction of stellar mass formed in the last 74 Myr, $M_{0-74\,\mathrm{Myr}}/M_*$. The dashed line is a fit to a dual component model $SNR = \alpha \times M_* + \beta \times M_{0-74\,\mathrm{Myr}}$. We find that β/α is non zero at the five-sigma level.

relative SN Ia rates per unit stellar mass for any subsamples we choose.

We follow this procedure for subsamples which are selected on their star formation history; we are looking for a correlation between the SN Ia rate and the recent star formation fraction. We found the most significant correlation when summing over the the last 74 Myr (the four most recent VESPA bins combined), as shown in Fig. 2.

Following Sullivan et al. ([33]), we fit a two-component model to these data, $SNR = \alpha M_* + \beta M_{0-74\,\mathrm{Myr}}$, where M_* is the total stellar mass and $M_{0-74\,\mathrm{Myr}}$ is the mass formed in the last 74 Myr. α and β reflect, respectively, the SNR per unit stellar mass of an old population of progenitors (proportional to the total stellar mass), and the SNR per unit stellar mass of a young population of progenitors (proportional to the mass in recently formed stars). Because our results are unnormalized, only the ratio β/α is meaningful: we find $\beta/\alpha = 465 \pm 83$, which is five-sigma evidence for a short duration component.

If there were some leakage of star formation from older bins (> 74 Myr) into the first four bins, then it would be possible that what we are calling the prompt SNe actually come from older progenitors. However, we see no evidence for this: star formation in older bins shows no correlation with SN rate, and increasing the number of bins from four to five (age < 115 Myr) simply reduces the correlation significance.

The effect of possible efficiency biases in the SN host sample will be discussed below (§4). Our results should be robust against possible spectroscopic calibration errors: because we compare the host population to a control sample of spectra taken with the same telescope and instrument, and processed with the same spectroscopic pipeline and the same star formation history recovery algorithm, calibration errors would be shared by the two samples.

The ratio β/α is compatible with previous estimates, for which the "recent" SFR is estimated in general from colors, broadband SED fitting, core-collapse SN rate or cosmic SFR. These results represent an average over half a gigayear, and are thus only a rough match to our results. We can roughly convert our mass estimate $M_{0-74\,\mathrm{Myr}}$ to recent SFR through $M_{0-74\,\mathrm{Myr}} = 74\times10^6 \frac{SFR}{1M_\odot\mathrm{yr}^{-1}} M_\odot$. With this, the Neill et al. (2006) values (a "slow" rate of $1.2\pm0.9\times10^{-14}$ SN $M_\odot^{-1}$ yr^{-1} and a "prompt" rate of $8.1\pm2.2\times10^{-4}$ SN $(M_\odot\mathrm{yr}^{-1})^{-1}\mathrm{yr}^{-1}$) yield $\beta/\alpha\simeq900$, the [33] values yield $\beta/\alpha\simeq100$, and the two values quoted by [31] yield $\beta/\alpha\simeq800$ and 400, respectively.

4. Discussion and conclusion

Our result would be sensitive to any systematic effect enriching the SN host sample in blue galaxies (i.e., those with large $M_{0-74\,\mathrm{Myr}}/M_*$), for reasons unrelated to SN physics (bias in efficiency, or bias in the monitored galaxy sample for targeted searches). Targeted searches could, for some reason, monitor a sample enriched in blue galaxies. In our sample, the main targeted search is the Lick Observatory Supernova Search (LOSS [7]) which contributes only 29 hosts; there is no indication this search is biased in this way, and our results change insignificantly if we remove those hosts.

Blue galaxies are fainter, and one could expect to detect SN more easily in those faint hosts, although with modern image differencing techniques, the effect should be minor. If host brightness were an important parameter, then SN detection would be less efficient close to galaxy centers. Such an effect has indeed been detected in SNLS [17], but is probably due to spectroscopic selection effects rather than raw detection efficiency, and is too small in any case to bias our results. In addition star-forming galaxies tend to produce brighter events. However: star-forming hosts tend to be dustier, which would make supernovae harder to detect. VESPA yields an estimate of dust content and luminosity of the host. We see no significant difference in luminosity and dust distributions between the host and control samples.

Following [18, 19, 33] we have shown that SNe Ia can occur through short-lived progenitors, hinting at a variety of stellar evolution paths with different lifetimes. We have given the first estimate of the lifetime of the "fast" component, by reconstructing the star formation history of SN host galaxies and finding an increased contribution to the SN Ia rate from stars evolving in less than 74 Myr.

Such a short time delay strongly constrains the nature of possible progenitors. They must be stars that evolve fast enough, i.e. with a mass above $\sim5.5M_\odot$, but must be below the super-AGB mass threshold (about 8 $M_\odot$) above which one gets electron-capture supernovae [27]. Pinsonneault et al. ([25]) have also suggested that a significant fraction of binaries are twins (i.e., pairs of stars with essentially identical masses), and that such twin binaries could produce a short (<0.1 Gyr) path to SN Ia. Considering common envelope evolution phenomena, Pinsonneault et al. ([25]) argue that such twin systems could yield double degenerate SNe Ia in a way that would be both fast and efficient (see also [9]).

Are there enough high-mass progenitors to account for the observed SNIa rate? These progenitors have to have masses between $5.5 M_\odot$ (in order to explode within 74 Myr) and $8 M_\odot$. Only a fraction of these stars f_β will actually explode as a SNIa progenitor. We take into account five factors: the fraction of stars in binaries (f_a), the fraction of the binaries both of whose components lie in the range 5.5 to 8 $M_\odot$ (f_b), the fraction of stars at a suitable separation for mass transfer (f_c), the fact that every binary yields a single explosion, (f_d), and an overall efficiency (η_β, as not all possible progenitors may explode). [20] has estimated the first four factors, and finds $f_a \in [2/3, 1], f_b \in [1/6, 1/3], f_c \in [1/4, 1/2]$ and $f_d = 1/2$. Multiplying these factors together gives the fraction of objects in the appropriate mass range that explode as prompt SN Ia: $f_\beta \in [0.014, 0.083]\eta_\beta$.

For a typical star-forming galaxy with total stellar mass $M_* = 10^{11} M_\odot$, $M_{0-74\,\mathrm{Myr}} \sim 10^8 M_\odot$. Assuming a Salpeter initial mass function of the form $dN/dm \propto m^{-2.53}$, the number of stars in this mass range which formed in the last 74 Myrs is $N_{[5.5,8]} \approx 0.0047 M_{0-74\,\mathrm{Myr}}/M_\odot$. Thus over 74 Myr, the supernova rate via the fast route is $\mathrm{SNR}_\beta = 6.4 \times 10^{-3} f_\beta$ SN yr^{-1}. A similar calculation for the slow route in the mass range of 3-8 $M_\odot$ over 10^{10} years gives: $\mathrm{SNR}_\alpha = 2.5 \times 10^{-1} f_\alpha$ SN yr^{-1}, where f_α is analogous to f_β for the slow route. Given that our experiment is not sensitive to absolute efficiencies, we can only constrain the ratio of efficiencies of the two mechanisms. Given our measure of the ratio of the fast and slow SN rates above, $\beta/\alpha = 465 \pm 83$, we find $\mathrm{SNR}_\alpha/\mathrm{SNR}_\beta = (\alpha/\beta)(M_*/M_{0-74\,\mathrm{Myr}}) \approx 2$. Equating this to the ratio of expressions above, and assuming that f_a, f_b, f_c and f_d are similar for the fast and slow routes, we find that the efficiencies η for the two routes are quite different: $\eta_\alpha/\eta_\beta = 0.05$. Thus most of the supernovae over the lifetime of the galaxy would be produced through the fast path, as was first suggested by [22].

Neill et al. ([21]) have estimated the rate of SN Ia via the slow route as $1.2 \pm 0.9 \times 10^{-14}$ SN$M_\odot^{-1}$yr^{-1}. Using the ratios above, this gives a rate for the fast route of $\mathrm{SNR}_\beta = 5.6 \pm 4.2 \times 10^{-4}$ SN yr^{-1}, which yields $f_\beta = 0.09 \pm 0.07$, in the range we determined from the values from Maoz (2007) above. Given the large error in the assumed slow rate and the uncertainty in the fraction of potential SNIa progenitors we conclude that there is no formal difficulty in finding enough progenitors to account for the rapid SNIa population, but there is a suggestion that the efficiency of production may be high.

A crucial question for the use of SN Ia as standard candles in cosmology is whether these different routes yield objects which are standardizeable to high accuracy via the same empirical corrections. Current data find no evidence for a difference [13, 32, 5], but the requirements for using SN Ia as a Dark Energy probe are stringent, and it will be important to establish this point accurately. VESPA should be able to assist directly with the correction, by identifying the star formation histories in detail, allowing better separation of SNe progenitors into prompt and long-lived populations.

We plan to expand our sample by obtaining spectra of a larger number of SN hosts, allowing us to deconvolve the delay time function. Future papers will address more quantitatively the long duration component, the metallicity effects (see also [28]), and stellar evolution models compatible with our findings.

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References

[1] Adelman-McCarthy, J. K. et al. 2007, ApJS, 172, 634

[2] Aldering, G. et al. 2004, arXiv:astro-ph/0405232

[3] Astier, P., Guy, J., Regnault, N., Pain, R., Aubourg, E., et al. 2006, A&A 447, 31

[4] Benford, D. & Lauer, T. 2006, SPIE, 6265, 626528

[5] Bronder, T. J., et al. 2007, arXiv:0709.0859

[6] Gallagher, J. S., Garnavich, P. M., Berlind, P., Challis, P., Jha, S. & Kirshner, R. P., 2005, ApJ 634, 210.

[7] Ganeshalingam, M. et al. 2007, in preparation

[8] Guy, J., Astier, P., Nobili, S., Regnault, N. & Pain, R., 2005, A&A 443, 781

[9] Hachisu, I., Kato, M., & Nomoto, K., 2007, arXiv:0710.0319

[10] Hamuy, M., Phillips, M.M., Maza, J, Suntzeff, N.B., Schommer, R. A., & Aviles, R., 1995, AJ 109, 1

[11] Hamuy, M., Phillips, M. M., Suntzeff, N. B., Schommer, R. A., Maza, J., & Aviles, R. 1996a, AJ 112, 2391

[12] Hamuy, M., Phillips, M. M., Suntzeff, N. B., Schommer, R. A., Maza, J., & Aviles, R. 1996b, AJ, 112, 2398

[13] Hamuy, M., Trager, S. C., Pinto, P. A., Phillips, M. M., Schommer, R. A., Ivanov, V. & Suntzeff, N. B., 2000, AJ 120, 1479, erratum 2001 AJ 122, 3506

[14] Howell, D. A., 2001, ApJ 554, L193

[15] Howell, D. A., Sullivan, M., Conley, A. & Carlberg, R., 2007, ApJ, 667, L37

[16] Jimenez, R., MacDonald, J., Dunlop, J. S., Padoan, P., & Peacock, J. A. 2004, MNRAS, 349, 240

[17] Lusset, V., PhD Thesis, Université Paris 7, 2006

[18] Mannucci, F., Della Valle, M., Panagia, N., Cappellaro, E., Cresci, G. et al., 2005, A &A 433, 807

[19] Mannucci, F., Della Valle, M. & Panagia, N., 2006, MNRAS 370, 773

[20] Maoz, D. 2007, MNRAS, submitted (arXiv0707.4598)

[21] Neill, J. D., et al. 2006, AJ, 132, 1126

[22] Oemler, A., Jr., & Tinsley, B. M. 1979, AJ, 84, 985

[23] Perlmutter, S., Aldering, G., Goldhaber, G., Knop, R. A. & Nugent, P., 1999, ApJ 517, 565

[24] Phillips, M., 1993, ApJ 413, L105

[25] Pinsonneault, M.H. & Stanek, K.Z., 2006, ApJ 639, L67

[26] Podsiadlowski, P., Mazzali, P. A., Lesaffre, P., Wolf, C., & Forster, F. 2006, arXiv:astro-ph/0608324

[27] Poelarends, A.J.T., Herwig, F., Langer, N., & Heger, A. arXiv:0705.4643

[28] Prieto, J.L., Stanek, K.Z., & Beacom, J.F., 2007, arXiv:0707.0690.

[29] Riess, A. G., Filippenko, A. V., Challis, P., Clocchiatti, A., Diercks, A. et al., 1998, AJ, 116, 1009

[30] Riess, A. G., Strolger, L.-G., Casertano, S., Ferguson, H. C., Mobasher, B. et al., 2007, ApJ, 659, 98

[31] Scannapieco, E., Bildsten, L., 2005, ApJ, 629, L85

[32] Sullivan, M., et al, 2003, MNRAS, 340, 1057

[33] Sullivan, M., Le Borgne, D., Pritchet, C. J., Hodsman, A. , Neill, J. D. et al., 2006, ApJ, 648, 868

[34] Timmes, F. X., Brown, E. F., & Truran, J. W. 2003, ApJL, 590, L83

[35] Tojeiro, R., Heavens, A. F., Jimenez, R., & Panter, B. 2007, MNRAS, 381, 1252

[36] Tripp, R. & Branch, D., 1999, ApJ 525, 209

[37] van den Bergh, S. 1995, ApJ, 453, L55

[38] Wood-Vasey, W. M., Miknaitis, G., Stubbs, C. W., Jha, S., Riess, A. G. et al, 2007, ApJ, 666, 694

[39] York, D.G. et al. 2000, AJ, 120, 1579

[40] Zheng, Z., & Ramirez-Ruiz, E. 2007, ApJ, 665, 1220