The Supernova Legacy Survey

Mark Sullivan[1]
Christophe Balland[2]

[1] Department of Physics, University of Oxford, United Kingdom
[2] Laboratoire de Physique Nucléaire et des Hautes Énergies (LPNHE), Centre National de la Recherche Scientifique (CNRS) – Institut Nationale de Physique Nucléaire et de Physique des Particules (IN2P3), Universités Paris VI and Paris VII, France*

The accelerating Universe was one of the most surprising discoveries of 20th century science. The 'dark energy' that drives it lacks a compelling theoretical explanation, and has sparked an intense observational effort to understand its nature. Over the past five years, the Supernova Legacy Survey (SNLS) has made a concerted effort to gather 500 distant Type Ia Supernovae (SNe Ia), a sample of standard candles with the power to make a 5 % statistical measurement of the dark energy's equation of state. The SNLS sample also provides one of the most uniform sets of SNe Ia available, with a photometric and spectroscopic coverage allowing new insights into the physical nature of SN Ia progenitors. With the survey recently completed, we report on the latest science analysis, and the vital role that the ESO VLT has played in measuring these distant cosmic explosions.

Type Ia Supernovae as cosmological tools

Type Ia Supernovae (SNe Ia) are a violent endpoint of stellar evolution, the result of the thermonuclear destruction of an accreting carbon-oxygen white dwarf star approaching the Chandrasekhar mass limit. As the white dwarf star gains material from a binary companion, the core temperature of the star increases, leading to a runaway fusion of the nuclei in the white dwarf's interior. The kinetic energy release from this nuclear burning – some 10^{44} J – is sufficient to dramatically unbind the star. The resulting violent explosion and shock wave appears billions of times brighter than our Sun, comfortably out-shining the galaxy in which the white dwarf resided.

SN Ia explosions are observed to explode with approximately the same intrinsic luminosity to within a factor of two, presumably due to the similarity of the triggering white dwarf mass and, consequently, the amount of nuclear fuel available to burn. These raw luminosities can be standardised further using simple empirical corrections between their luminosity, light-curve shape and colour – intrinsically brighter SNe Ia typically have wider (slower) light curves and a bluer optical colour than their fainter counterparts (e.g. Phillips, 1993). The combination of extreme brightness, uniformity, and a convenient month-long duration, makes SNe Ia observationally attractive as calibrateable standard candles; objects to which a distance can be inferred from only a measurement of their apparent brightness on the sky. Applying the various calibrating relationships to SN Ia measurements provides distance estimates precise to ~ 7 %, which can be used via the redshift-magnitude relation (or Hubble Diagram) to determine cosmological models.

For many years following the realisation of the cosmological potential of SNe Ia, finding distant events in the numbers required for meaningful constraints was a considerable logistical and technological challenge. Years of searching were required to discover only a handful of SNe Ia (e.g. Perlmutter et al., 1997). The field only matured with the advent of large-format CCD cameras capable of efficiently scanning large areas of sky, and the simultaneous development of sophisticated image processing routines and powerful computers capable of rapidly analysing the volume of data produced. The substantial search effort culminated in the late 1990s when two independent surveys for distant SNe Ia made the same remarkable discovery: the high-redshift SNe Ia appeared about 40 % fainter – more distant – than expected in a flat, matter-dominated Universe (Riess et al., 1998; Perlmutter et al., 1999), providing astonishing evidence for an accelerating Universe. When these observations were combined with analyses of the cosmic microwave background, a consistent picture emerged of a spatially flat Universe dominated by a dark energy responsible for ~ 70–75 % of its energy, opposing the slowing effect of gravity and accelerating the Universe's rate of expansion.

This incredible discovery sparked an intense observational effort: at first to confirm the seemingly bizarre and unpredicted result, and later to place the tightest possible observational constraints on dark energy, in the hope that a theoretical understanding could follow. Many hundreds of SNe Ia have now been discovered out to a redshift of 1.5 in an effort to map the Universe's expansion history, and alternative cosmological probes have been developed and matured: understanding dark energy has become a key goal of modern science.

The Supernova Legacy Survey

The five-year Canada-France-Hawaii Telescope (CFHT) Supernova Legacy Survey (SNLS) started in mid-2003 with the ambitious goal of discovering, confirming and photometrically monitoring around 500 SNe Ia to determine the nature of dark energy. The development of the square-degree imager MegaCam on the 3.6-m CFHT, and the efficiency with which it could survey large volumes of sky, meant that SNe Ia out to $z = 1$ could be discovered routinely and essentially on demand. The multi-band optical data (Figure 1) comes from the Deep component of the CFHT Legacy Survey (CFHT-LS), observing each of four fields every three or four days during dark time in a rolling search for around six lunations per year. As optical transient events are discovered, the repeated imaging automatically builds up high-quality light curves which can be used to measure the SN peak brightnesses, light-curve

* The full SNLS core collaboration is: Pierre Astier (LPNHE, CNRS-IN2P3), Dave Balam (University of Victoria), Christophe Balland (LPNHE, CNRS-IN2P3), Stephane Basa (LAM), Ray Carlberg (University of Toronto), Alex Conley (University of Toronto), Dominique Fouchez (CPPM), Julien Guy (LPNHE, CNRS-IN2P3), Delphin Hardin (LPNHE, CNRS-IN2P3), Isobel M. Hook (University of Oxford), Andy Howell (University of Toronto), Reynald Pain (LPNHE, CNRS-IN2P3), Kathy Perrett (University of Toronto), Chris J. Pritchet (University of Victoria), Nicolas Regnault (LPNHE, CNRS-IN2P3), Jim Rich (CEA-Saclay), Mark Sullivan (University of Oxford).

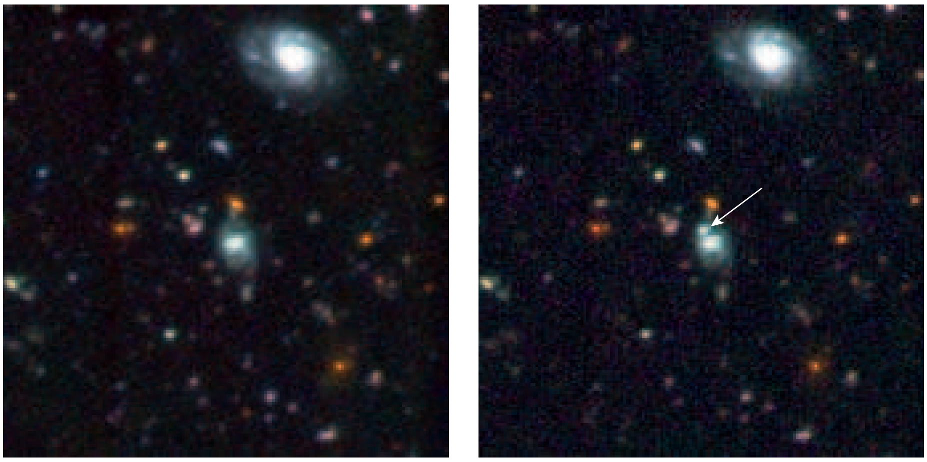


Figure 1. The point of light marked on the right image is a distant Type Ia Supernova, nearly four billion light-years away at a redshift of 0.31. This false-colour image is generated from *g′*, *r′* and *i′* data taken using MegaCam at the 3.6-m Canada-France-Hawaii Telescope on Mauna Kea. Once these transient events have been located, they can be spectroscopically confirmed by 8-m-class telescopes such as the ESO VLT.

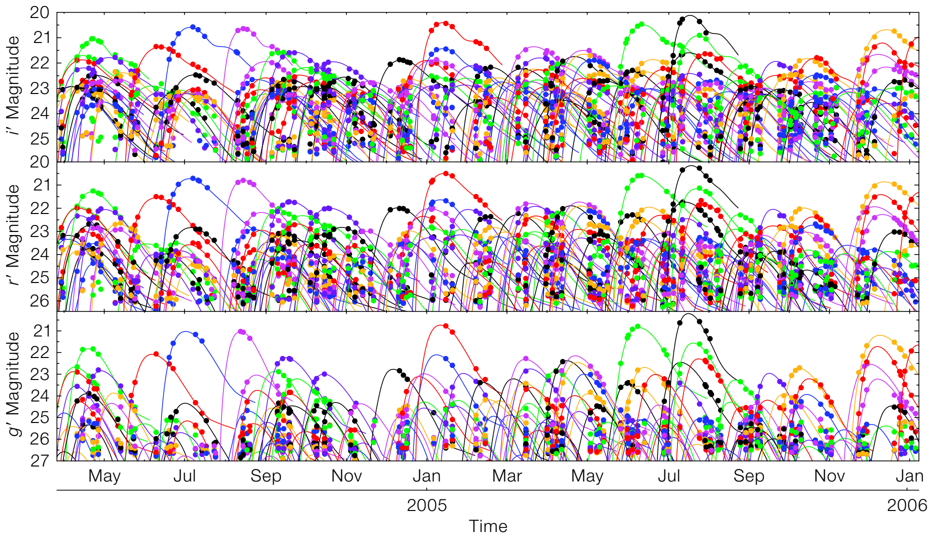


Figure 2. The light curves of more than 150 SNe Ia, discovered and photometrically monitored by CFHT. Each point represents a single MegaCam observation (several SNe are observed simultaneously due to that instrument's wide field of view). The solid curves are light-curve template fits to each SN and are used to interpolate the brightness at maximum light for the subsequent cosmological analyses (e.g. Astier et al., 2006). The three panels show data taken in the *i′* filter (upper), *r′* (middle) and *g′* (lower). *z′* data is also taken but is not shown. The multi-band data is essential for both accurate *k*-corrections to the rest-frame, and for measurement of the optical colour of the SN at maximum light.

widths, and colours required for the cosmological analysis (Figure 2). In addition, a vast database of deep and accurate photometry yielding well-sampled multicolour light curves for all classes of optical transients is available.

The role of the VLT

A critical component of any SN survey is spectroscopic follow-up of candidate events, confirming their nature and measuring the redshifts essential for placement on a Hubble Diagram. The SNLS is no exception. Being optically faint – fainter than 24th magnitude at a redshift of one – distant SN spectroscopy requires the light-collecting power of 8-m-class telescopes, such as the ESO VLT. As with all transient events a rapid response is essential while the SN Ia candidate remains optically bright. Our ESO/VLT real-time follow-up (Basa et al., in prep.) has used ToO mode with FORS1 and FORS2 (Appenzeller et al., 1998), the latter for the higher-redshift candidates where the sensitive red response becomes more critical. In general, FORS1 was operated in MOS mode with the moveable slits, observing not only the principal transient target, but the host galaxies of several other old variable events, the light from which has since faded. This multiplexing has resulted in a large number of redshifts of transients as well as spectra of the SNe Ia.

Over the duration of two ESO large programmes, we have followed up nearly 320 optically transient events, and with the last six months of data still being analysed, have confirmed 200 as SNe, and more than 160 as SNe Ia (see examples in Figure 3). When the analysis is complete, this number is expected to rise to more than 200, representing the largest number of SNe Ia confirmed with a single telescope. This will be a dataset with considerable legacy value, not only for studying dark energy, but also for learning about the physics of the SN explosions themselves.

VLT spectra represent a large fraction of the SNLS SNe Ia spectra, and considerable work has been done to produce a clean identification of their types and redshifts, necessary for their subsequent cosmological use. In particular, two new techniques have been developed for our VLT spectra. The first is a dedicated pipeline that makes use of photometric information during the spectral extraction phase (Balland et al., in prep.). Distant SNe Ia are often buried in their host gal-

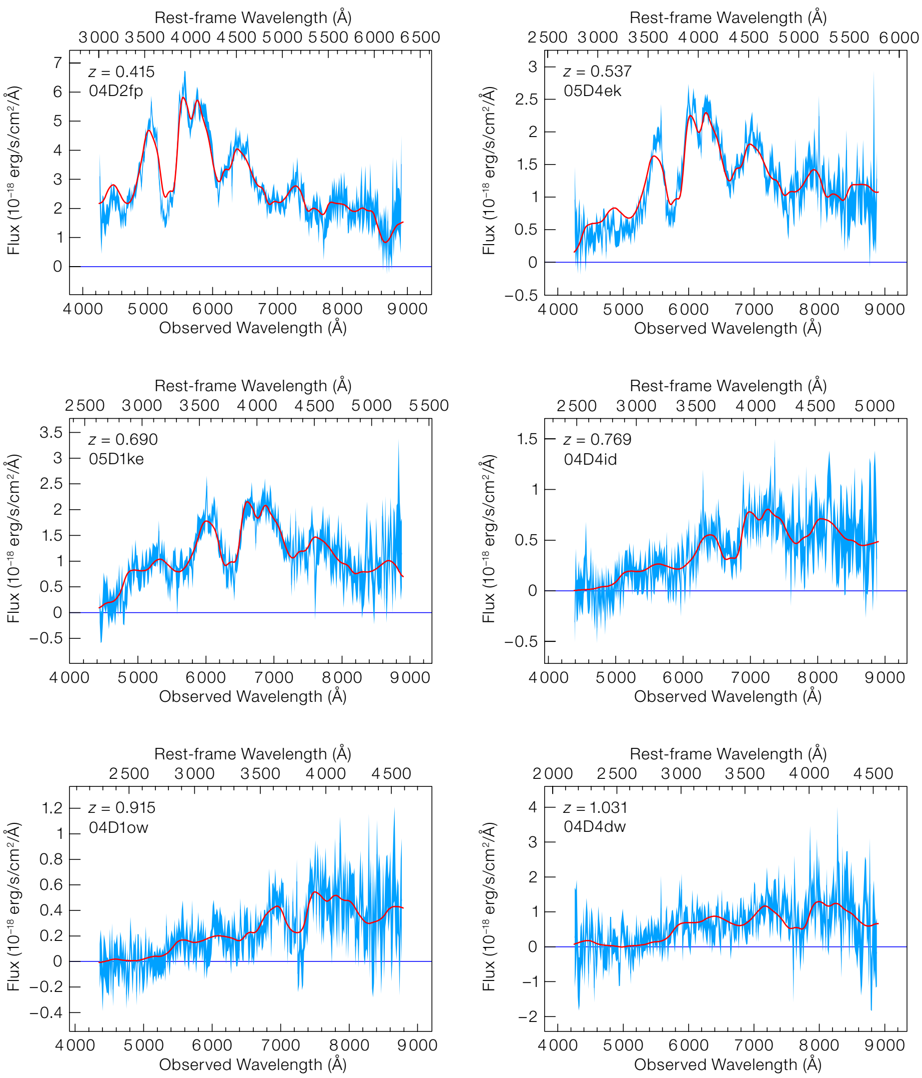


Figure 3. Example spectra of SNe Ia from the VLT/FORS follow-up campaign (Balland et al., in prep). Each panel shows a different SN Ia distributed over $z \simeq 0.4$ to $z \simeq 1$. In each case the blue line is the observed FORS spectrum, and the red the model template fit. The characteristic Ia features allow robust SN classifications, and in the spectra with a higher signal-to-noise, the chemical features can also be used to study the redshift evolution of SN Ia properties.

axies, with light from the continuum of the galaxy drowning out signal from the SN, making the task of SN identification difficult (Figure 4). The spatial profile of the host galaxy is measured from MegaCam images in several photometric bands projected along the slit and then matched to the spectral profiles from FORS at the corresponding wavelengths. This technique allows a precise estimate of the host contamination at the SN position, optimally recovering the spectra of both the SN and its host. If the SN is too close to its host galaxy centre for a separate extraction, the combined spectrum is extracted and fit to a two-component model comprising a spectral model of the SN Ia and a galaxy model drawn from a large set of template spectra spanning the Hubble sequence. The left panel of Figure 4 shows an example of such a fit, with the spectrum of this distant SN well measured despite its location in the core of its host.

The second technique concerns the spectral identification. This uses a spectrophotometric model of SNe Ia constructed from a sample of both nearby and distant SNe covering a wide range of epochs. Each new SN candidate spectrum is fit to this model, and the best-fit parameters are compared on a case-by-case basis to the average properties of the SN Ia model sample. Differences are interpreted as the signature of peculiar or non SNe Ia spectra. Although the final identification relies on human judgement, this procedure limits the subjectivity usually entering SN classification.

The resulting clean, host-subtracted SN Ia spectra can be used to analyse any evolution in the strength of the SN chemical features with redshift, placing constraints on the degree to which the SNe themselves change with cosmic time. This is one of the most direct methods available for probing any changing composition of the SN Ia progenitors.

Cosmological measurements

The key measurement made by the SNLS is the determination of the equation of state of the dark energy, w, the ratio of its pressure to energy density. Dark energy must have a strong negative pressure to explain the observed cosmic acceleration and hence have a negative w. The sim-

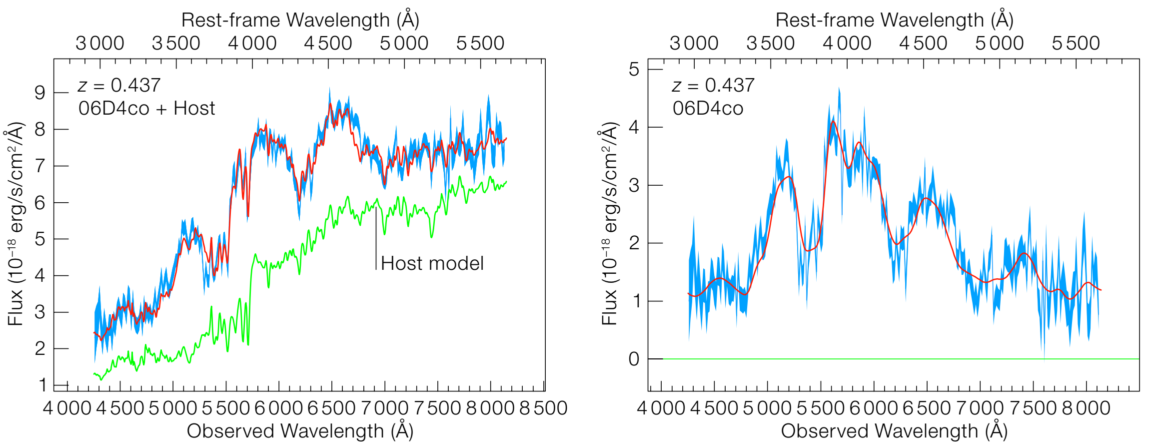


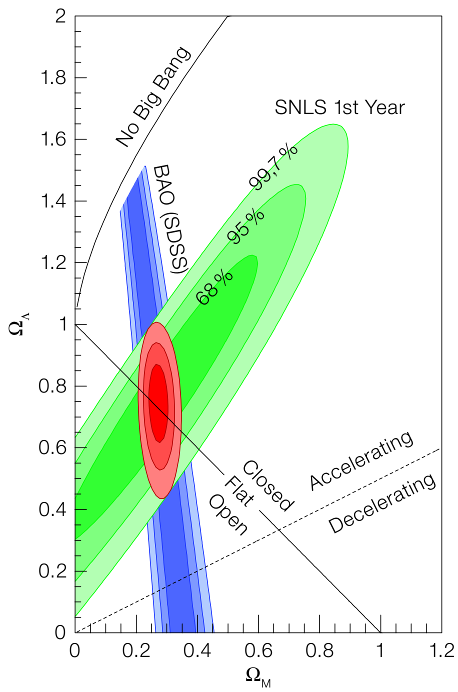
Figure 4. An example of host galaxy subtraction techniques developed for analysing VLT/FORS spectra of SNLS SNe Ia. The left panel shows the raw spectrum (blue) and model fit (red), together with the best-fitting host galaxy spectrum (green). Once the host galaxy is subtracted (right panel), the spectrum is ready for both classification and science analysis.

plest explanation is a Cosmological Constant, an intrinsic and non-evolving property of empty space with a negative pressure equal to its energy density such that $w = -1$. Other ideas include the broad family of quintessence models, which predict a dynamic and varying form of dark energy field generally with $w \neq -1$, and phantom energy, a form of dark energy with $w < -1$ that would ultimately tear apart all gravitationally bound structures in a 'big rip' (for a detailed review of the different possibilities see Copeland et al., 2006). An alternative considered by some theorists is that the cosmologist's fundamental tool, General Relativity, may simply fail on very large scales.

SNe Ia are used to measure cosmological parameters by comparing their standard candle distances (derived from their apparent brightnesses and a knowledge of the SN Ia absolute luminosities) with luminosity distances calculated from their redshifts together with a set of cosmological parameters and the equations of General Relativity. As the cosmological parameters are, in principle, the only unknowns in this analysis, constraints can be placed on their values with a sufficient number of SNe Ia.

This apparently simple concept has several non-apparent difficulties. Measuring departures in dark energy from $w = -1$ requires an extremely precise experiment: a 10 % difference in w from –1 is equivalent to a change in SN Ia brightness at $z = 0.6$ of only 0.04 magnitudes, an absolute precision perhaps not routinely achieved in astronomy. The challenge of photometrically calibrating the physical SN fluxes, as well as empirically controlling the various light-curve width and colour relations, is therefore considerable. Furthermore, the values of the other cosmological parameters that enter the luminosity distance calculation, such as the matter density or amount of curvature in the Universe, are not perfectly known. Other complementary observations must be used in conjunction with SNe Ia (see Figure 5) which place constraints, or priors, on the matter density (e.g, observations of large-scale structure) or spatial flatness (e.g., observations of the Cosmic Microwave Background). Finally, the absolute luminosity of a SN Ia is not known precisely and cannot be used a priori. The SN Ia method critically relies on sets of local SNe at $0.015 < z < 0.10$, where the effect of varying the cosmological parameters is small, and which essentially anchor the analysis and allow relative distances to the more distant events to be measured.

The cosmological analysis of the first year SNLS dataset (SNLS1) is published in Astier et al., 2006; the key results are shown in Figure 5. The result, $\langle w \rangle = -1.023 \pm 0.090$ (statistical error), is consistent with a cosmological constant (i.e., $w = -1$) to a better than 9 % precision. Analyses of SNLS3, the third-year sam-



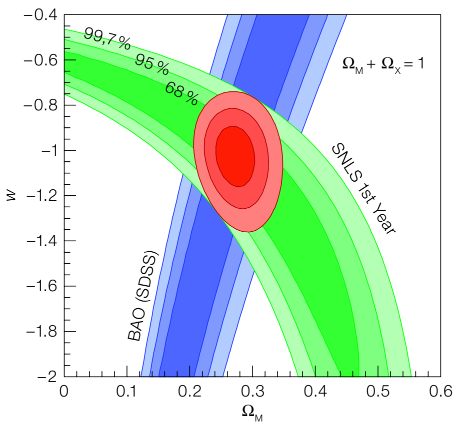


Figure 5. Cosmological constraints from SNLS1. On the left are the cosmological constraints in Ω_M versus Ω_Λ (assuming $\langle w \rangle = -1$), and on the right the constraints in Ω_M versus $\langle w \rangle$ (assuming a flat Universe and a constant equation of state w). The best-fitting result was $\Omega_M = 0.263 \pm 0.042$ for a flat ΛCDM model, and $\langle w \rangle = -1.023 \pm 0.090$ for a flat cosmology with a constant w. The statistical error in $\langle w \rangle$ of 9 % will improve to better than 6 % in the upcoming SNLS3 papers.

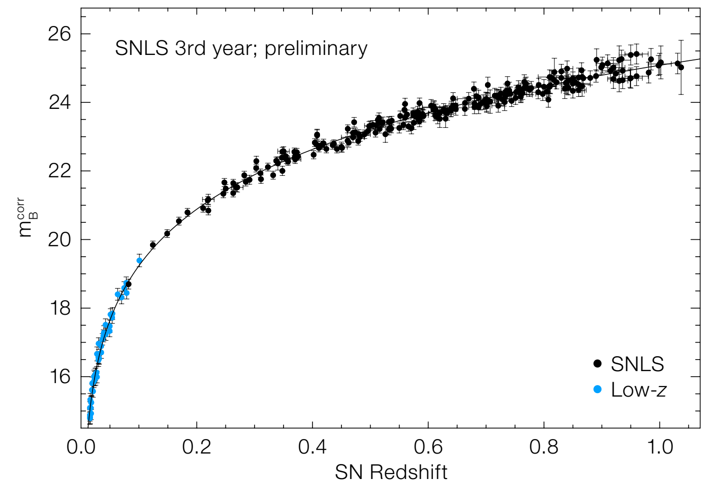


Figure 6. The preliminary Hubble Diagram from the SNLS3 analysis. Each black filled circle represents a SN detected and monitored at the CFHT, and spectroscopically confirmed using 8–10-m class facilities such as the ESO/VLT. The blue circles are the lower-redshift comparison sample which anchor the Hubble diagram analysis.

ple, are now nearing completion (a preliminary Hubble Diagram can be found in Figure 6). With a sample size three times larger than SNLS1, the analysis provides not only a step forward in the statistical precision, but in the understanding of SNe Ia as astrophysical events, and will lead to a better than 6 % constraint on ⟨*w*⟩. A ~ 5 % measurement of ⟨*w*⟩ is expected from the final SNLS sample, as well as the first detailed measurements of the degree to which *w* changes out to $z = 1$.

Supernova astrophysics

Taken at face value, the simplicity of the SN Ia technique – comparing the relative brightnesses of events at different distances – suggests the ultimate accuracy of their use may only be limited by the extent to which relative calibrations of their fluxes can be performed. This may, however, be an over-simplification, and would ignore the considerable uncertainty that exists over the underlying physics governing SN Ia explosions. For example, the configuration of the progenitor system prior to explosion is very uncertain. Both single degenerate systems (a white dwarf star together with a main-sequence or red-giant companion) or double degenerate systems (two white dwarf stars) could theoretically result in a SN Ia explosion. There are also open questions as to how the metallicity or age of the progenitor star may influence the observed properties of the SN explosion, leading to possible biases as the demographics of the SN Ia population shifts slightly with look-back time.

The SNLS has provided some new insight into these issues. The homogeneous nature of the CFHT-LS data provides not only precise SN light curves, but also extremely deep image stacks from which SN Ia host galaxy information can be obtained (Sullivan et al., 2006). Analyses of these data allow the measurement of galaxy properties such as stellar mass, star formation activity and mean age, and subsequent studies of how SN Ia properties relate to these different variables.

In particular, the classical view that most SNe Ia result from old, evolved stellar populations appears incorrect. Although some SNe Ia do occur in passive systems with little or no recent star formation activity, consistent with a long delay time from stellar birth to SN explosion, most seem to occur in actively star-forming galaxies, suggesting a short delay time (Figure 7; see also Sullivan et al., 2006). These prompt and delayed SNe Ia possess different light curves: prompt SNe Ia appear brighter with broader light curves, while the delayed component SNe are fainter with fast light curves. By virtue of the evolving mix of quiescent and star-forming galaxies with redshift, a subtle redshift evolution in SN Ia population demographics is predicted (Figure 7) and has now been observed in SNLS data (Howell et al., 2007). Although such shifts do not affect cosmological conclusions if the SN Ia calibrating relationships remain universally applicable, further analysis of the SNLS dataset is required to test this assumption.

The most straightforward interpretation of this environmentally-dependent SN Ia rate is a wide range of delay times, but the exact physical implications are un-

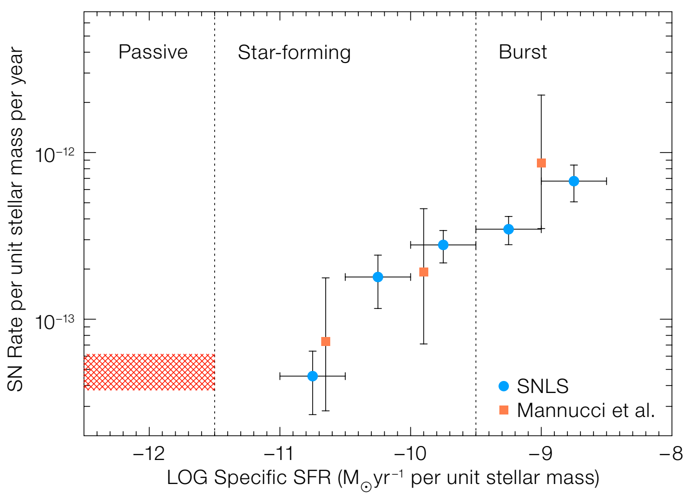


Figure 7. SNLS has provided evidence that SN Ia properties are dependent on the age of the progenitor system. The SN Ia rate per unit stellar mass *versus* host star-formation rate per unit stellar mass (Sullivan et al., 2006). Blue points refer to SNLS data, orange points to local estimates. The red area indicates the SNLS SN Ia rate in passive, or zero star-formation rate, galaxies. A SN Ia population with a wide range of delay times is supported: simplistically, a delayed population in quiescent galaxies together with a prompt population whose rate correlates with recent star formation.

clear. The SNLS relation between SN Ia rate and star-formation rate (Figure 8) implies that around 1 % of all white dwarfs end their lives as SNe Ia (Pritchet et al., 2008), independent of their initial mass. As the single degenerate model typically has lower conversion efficiencies at lower masses, this suggests that some other mechanism is responsible for the production of at least some SNe Ia. However, the precise implication for the progenitor systems must await the construction of a more detailed delay-time distribution.

Future perspectives

The upcoming analysis of the SNLS third year dataset will provide the most precise measurement yet of the nature of the dark energy driving the accelerating cosmic expansion. While these cosmological results will inevitably draw most attention, SNLS has also allowed new insights into the astrophysics governing SN Ia progenitors and their explosions. To date, no effect has been uncovered that challenges the conclusions that have been drawn from using SNe Ia in cosmological applications, but some open questions remain. Why are the brightest SNe Ia associated with short delay times and the youngest galaxies? How well do SNe Ia from different environments inter-calibrate in a cosmological analysis? A tantalising possibility is the existence of *more than one progenitor mechanism* (e.g. Mannucci et al., 2006). The key to making progress is to pinpoint any fundamental environmental differences between delayed and prompt events. For example, metallicity is predicted to affect SN Ia luminosities and rates. Timmes et al. (2003) predict that higher metallicity progenitors produce white dwarfs richer in ^{22}Ne, with an increased neutronisation during nuclear burning producing stable ^{58}Ni at the expense of the ^{56}Ni that powers the light curves. As a result, a $\leq$ 25 % difference in luminosity is expected between high and low metallicity environments. Recent observational results hint at these effects (Gallagher et al., 2008), but urgently need confirmation with detailed spectroscopy of the host galaxies of larger, complete and homogeneous samples, such as the SNLS. Such a programme will soon commence using the VLT.

As with any experiment, the final precision of the SNLS results is governed by both statistical and systematic uncertainties. As more SNe Ia are used in the analysis and the statistical error decreases, the contribution of systematic errors becomes increasingly important. Ultimately, the challenge of controlling systematics in SN cosmology is two-fold. The first is photometric calibration. The SNLS calibration is accurate to about 0.01–0.015 magnitudes; future, planned experiments will require a calibration of better than 1 % in both the distant and nearby sample – as much effort is required for the local sample as was needed for the higher-redshift SNLS dataset. The second challenge is understanding the limitations of SN Ia by investigating their astrophysical properties and controlling any subtle evolutionary effects. SNLS is providing the essential stepping stone for both efforts.

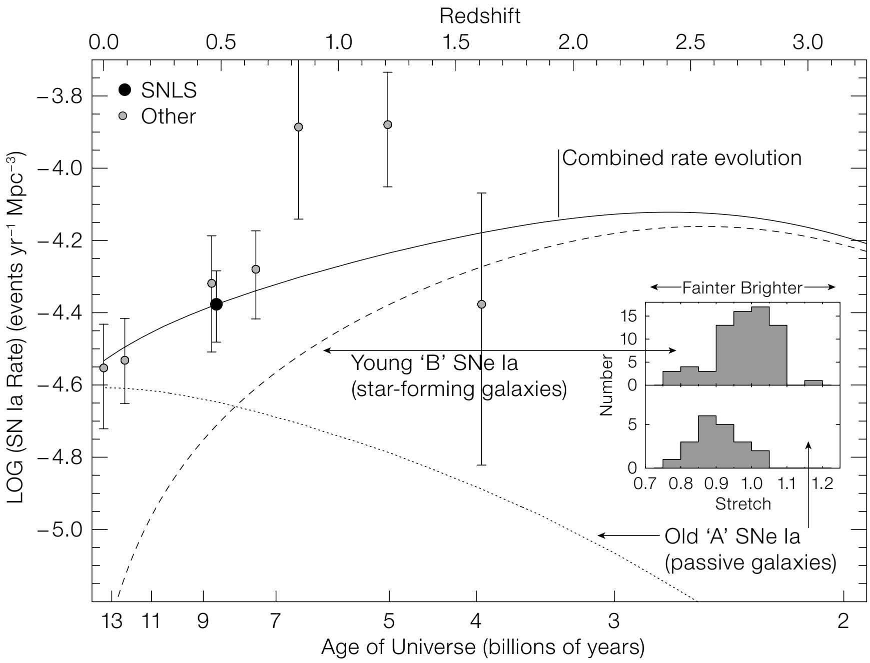


Figure 8. The volumetric SN Ia rate redshift evolution derived from the SNLS SN Ia properties. The relative mix of the two components will evolve with redshift (main panel). As SN light curve width ('stretch') correlates with star-formation activity in the host (inset histograms), a mild evolution in mean SN Ia lightcurve width with redshift is implied as the relative mix of the two components changes. This effect has been detected in SNLS data (Howell et al., 2007), and must be carefully controlled in Hubble diagram analyses.

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