SUPERNOVA PHYSICS WITH THE SUPERNOVA LEGACY SURVEY

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The set of observations of the SuperNova Legacy Survey (SNLS) allowed supernova physics to be studied. SN Ia progenitor scenarios were addressed as well as the connection between progenitor properties and SN Ia luminosities. Besides SNe Ia, the sample of SNLS data also contain core-collapse supernovae, the rate of which was measured with great accuracy. Results on these topics, based on the first three years of the survey, are hereafter reviewed.

1 Introduction

SNLS was in operation from 2003 to 2008 at the Canada-France-Hawaii telescope in Hawaii. The project relied on the excellent sky at the Mauna Kea site, on an optimized observing strategy and on the MegaCam imager, a one-square degree CCD camera array of 340 million pixels. Four one-square degree fields of view were repeatedly imaged every 3 or 4 nights during dark time, allowing multi-colour light curves to be measured with very good time sampling in four broadband filters from 400 to 1000 nm. The images were also used to measure properties of the supernova (SN) host galaxies, such as total stellar mass, star formation rate or host galaxy redshift. In addition, the project was allocated a large amount of spectroscopic time on 8-10 m class telescopes in order to derive precise SN types and redshifts. This review presents results on supernova physics based on the 3-year data sample of the SNLS, which amounts to about 250 SNe Ia with spectroscopic identification in the redshift range $0.1 < z < 1.2$.

2 SN Ia progenitor models

SN Ia light curves and spectra being rather reproducible, a common scenario is believed to dominate their production. In this scenario, called the single-degenerate (SD) model, the supernova progenitor is a carbon-oxygen white dwarf (WD) in a close binary system, which accretes mass from its giant companion. When the Chandrasekhar mass is approached, the WD core temperature rises, carbon fusion is ignited and the WD undergoes runaway nuclear fusion, which disrupts it. The nuclear reactions stop with ^{56}Ni production and are followed by the radioactive decay of this element through ^{56}Co to ^{56}Fe which generates the supernova luminosity. Observational facts in favour of this model are the lack of hydrogen in SN Ia spectra, the SN Ia light curve shape, their reproducible luminosity and the occurrence of SNe Ia in old stellar populations.

In order to test the SD model further, SNLS measured the SN Ia rate as a function of the star formation rate (SFR) of the host galaxy [1], both rates being normalized per unit galactic stellar mass. As shown in the lefthand plot of Figure 1, SNe Ia occur in passive galaxies, as expected since white dwarves represent the end of stellar evolution for low to intermediate mass

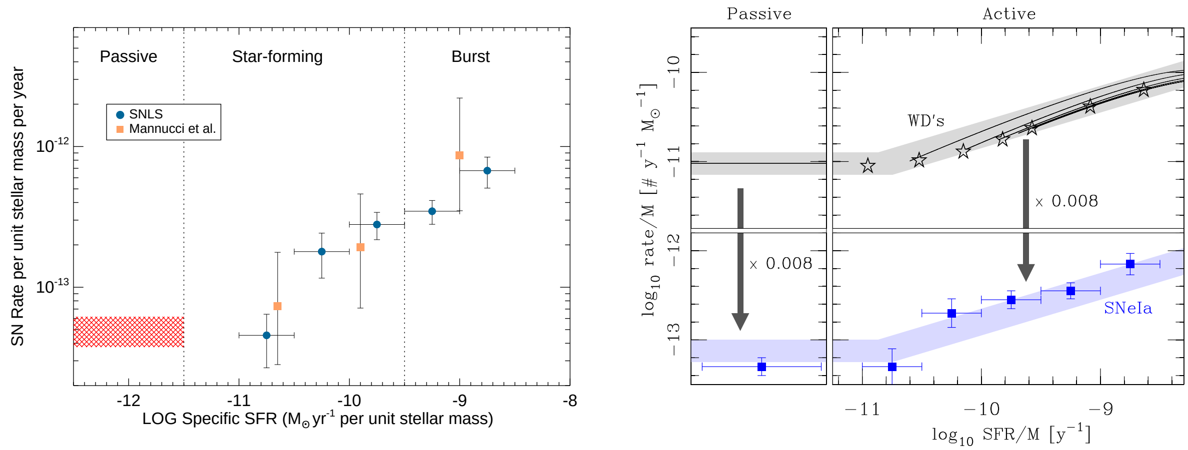

Figure 1: Left: SN Ia rate as a function of the host galaxy star formation rate. SNLS results (hatched band and filled circles) are compared with results from low redshift SNe (filled squares). Right: White dwarf formation rate computed for systems with various star fomation history (solid lines and stars in upper plot) as a function of the star formation rate. Once down-scaled by a factor 0.008, the locus of the predictions (blue band) agrees with the observed SNLS SN Ia rate (squares in bottom plot).

stars (1 to 8 solar masses), but they are also observed in active, star-forming and thus younger systems. Moreover, the explosion rate increases strongly with the SFR.

To test whether the SD channel is able to reproduce this result, the WD formation rate was computed from a great variety of WD models, including systems with rising or decreasing SFR, starburst systems or composite stellar populations with an old passive bulge and halo and a star-forming disk[2]. The result, in the righthand plot of Figure 1 shows that there is little spread in the normalized WD formation rate at a given SFR, indicating that this rate depends mostly on the star age but is insensitive to details of the star formation history of the environment like the initial mass function (IMF). In addition, the normalized WD rate does increase as the mean age of the stellar population decreases. This results from the fact that, even in the presence of a steeply-sloped IMF favouring low mass stars, the evolutionary timescales of intermediate mass stars are much shorter than that of low mass stars, resulting in a large WD rate even in young systems. Last, the modelled WD formation rate and the observed SN Ia rate have similar evolutions with the SFR, the SN Ia rate being 0.8% of the WD formation rate.

To account for the evolution of the companion star into the state of a giant star, WD formation models were convoluted with different time delay distributions, based on different distributions of the mass ratio between the companion star and the WD. Any difference between the modelled rate and the observed SN Ia rate would then be attributed to the probability for the evolved binary system to end up into an explosion. Comparing the modelled rate with the observed SN Ia rate, a conversion efficiency of 1.5% is obtained (within a factor 2), in agreement with other determinations which are all more uncertain. Moreover, a uniform (i.e. SFR-independent) 1.5% conversion efficiency provides agreement with the observed dependence of the SN Ia rate with the SFR. This is a surprise, since low mass stars, and thus galaxies with low or no star formation, are expected to have lower WD conversion efficiencies. It is thus likely that in these galaxies, another scenario competes or even dominates the SD channel. Disentangling their individual contributions remains to be done. The 1.5% conversion efficiency thus holds for any progenitor mass range dominated by the SD channel.

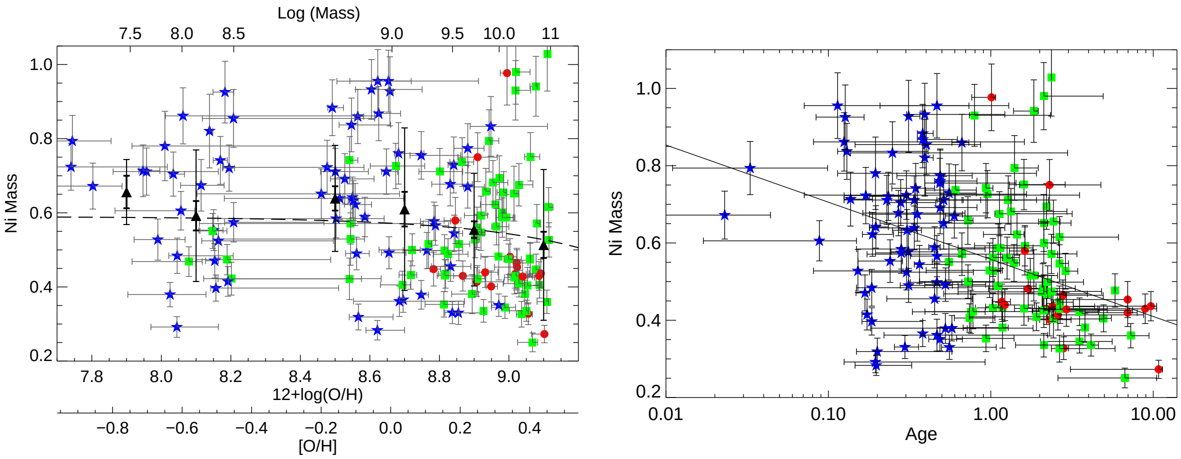

Figure 2: ^{56}Ni yield as a function of the host galaxy metallicity (left) and age (right). SN Ia data from SNLS have been divided in 3 subsets according to host stellar activity (passive hosts: red dots, active hosts: green squares, burst galaxies: blue stars). The dashed line in the lefthand plot is the theoretical prediction for the average Ni yield. The solid line in the righthand plot is a fit to the data.

3 SN Ia luminosities and progenitor age

Intrinsic SN Ia peak luminosities are reproducible within about 40%. For precise cosmology results, this scatter is reduced by applying empirical corrections. A residual spread of around 15% is obtained, thus allowing distance luminosities from SNe Ia to be used to constrain cosmology. Understanding the physics origin of this intrinsic spread is of primary importance to reduce the systematic uncertainties in the use of SNe Ia as cosmological probes.

SNLS studied the ^{56}Ni yield in type Ia SNe, as deduced from their light curves, as a function of their progenitor properties, estimated from those of the host galaxies [3]. As an example, the lefthand plot in Figure 2 shows the ^{56}Ni yield as a function of the host galaxy metallicity, which is believed to have a great influence on the SN luminosity. The Ni mass (and thus the supernova intrinsic brightness) is observed to decrease in high metallicity galaxies, which can be explained by the production of more neutron-rich nuclides (^{58}Ni or ^{54}Fe) during the explosion of metal-rich progenitors, at the expense of radiocative ^{56}Ni. The observed decrease in Ni yield agrees on average with the theoretical expectation, but the scatter in Ni mass at a given metallicity is much higher than the average drop, indicating that metallicity effects account only for a small part, about 10%, of the scatter in SN Ia intrinsic luminosities.

The righthand plot in Figure 2 shows the ^{56}Ni yield as a funtion of the host galaxy age. The decrease in Ni mass and thus in luminosity is strongly correlated with the age of the host galaxy, suggesting that the mass of the companion star has an impact on the SN luminosity. More generally, the binary system evolution and mass transfer history, which depends on the companion mass, may influence the outcome of the explosion.

4 Core-collapse rate at $z \sim 0.55$

Besides SNe Ia, SNLS is sensitive to core-collapse supernovae, which are the usual fate of high mass stars (above 8 solar mass). As core-collapse SNe are on average 1.5 magnitude fainter than SNe Ia and as the SNLS sample with spectroscopic identification is dominated by SNe Ia, a purely photometric analysis of SNLS data was performed in order to select core-collapse (CC) events. The analysis was restricted to $z < 0.4$ where the CC sample is almost complete and the contamination is negligible [4]. The lefthand plot in Figure 3 illustrates the clear separation between SN Ia and CC events in the magnitude vs redshift plane. Spectroscopic and photometric

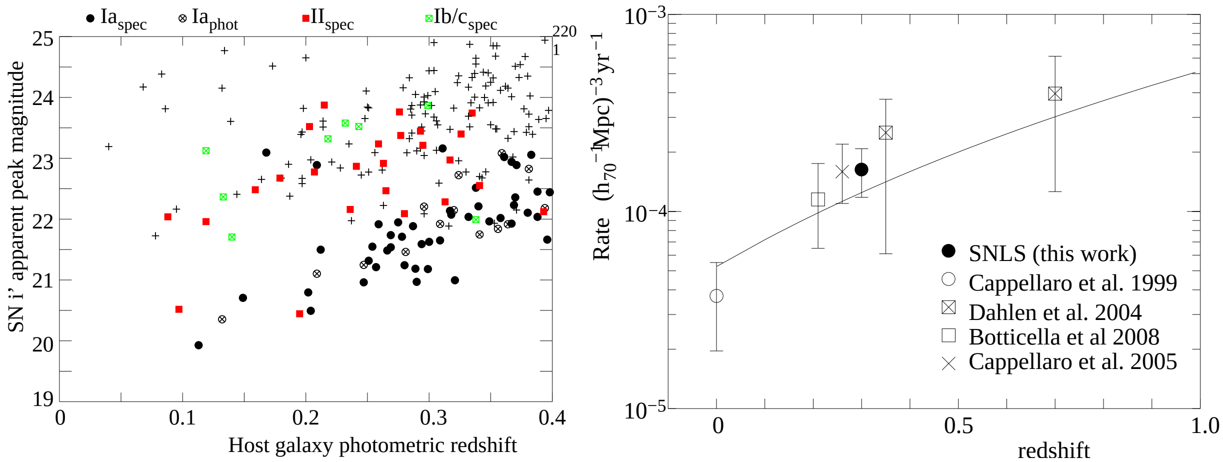

Figure 3: Left: Photometrically selected events in the magnitude vs redshift plane. Filled symbols stand for events with spectroscopic identification. Right: Measurements of the core-collapse supernova rate as a function of redshift. The solid line is a fit to data of the form $(1+z)^{3.6}$ as expected from the star formation rate at $z < 0.5$.

typing of SNe Ia was nonetheless used to define the two sets of Ia and CC supernovae. Properties of the two sets of events were studied. In both samples, photometric events have properties (light curve fall time, colour) similar to those of events with spectroscopic identification.

The magnitude distributions of the two subsamples, once corrected for volume effects and detection efficiency, allowed the ratio of the CC to SN Ia rates to be determined. In the range of sensitivity of the analysis, the rate ratio is found to be $4.5 \pm 0.8(stat.)^{+0.9}_{-0.7}(syst.)$. Using the SN Ia rate measured by SNLS[6] and correcting the CC magnitude distribution for host absorption (following the model of[5]), the absolute value of the CC rate was derived. The result is shown in Figure 3 where the SNLS measurement, together with other (less precise) measurements at different redshifts, allow the redshift dependence of the CC rate to be tested. A dependence proportional to $(1 + z)^{3.6}$, as observed for the star formation rate at $z < 0.5$, does reproduce the evolution of the CC rate. The rate of core-collapse supernovae thus seems to follow the star formation rate, while the SN Ia rate evolves only like the square root of the latter.

5 Conclusions

The large sample of SNLS data allowed studies on supernova physics to be made. The standard SN Ia progenitor scenario, based on a white dwarf accreting mass from a giant companion star reproduces observations of the SN Ia rate once stellar evolutionary timescales are taken into account. The intrinsic dispersion of SN Ia luminosities is explained only partly by progenitor metallicities, while the mass of the companion star seems to have a larger influence. The rate of core-collapse SNe was measured by SNLS with the best precision to date, and, in combination with other measurements, was found to increase with the redshift like the star formation rate.

References

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