SUDARE at the VST

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The SUpernova Diversity And Rate Evolution (SUDARE) programme on the VLT Survey Telescope aims to collect an unbiased and homogeneous sample of supernovae (SNe) in all types of galaxies out to redshift ~ 0.6. In four years, around 500 Type Ia and core-collapse SNe are expected to be discovered, including significant numbers of rare SN types. The programme is outlined and 100 SNe candidates have already been detected in the first year of the programme. Follow-up spectroscopy of the SN candidates, an important aspect of the programme, is also described.

Despite the key role played by supernovae in discovering the accelerating expansion of the Universe (Perlmutter et al., 1998; Riess et al., 1998) there are still basic questions to answer about SN progenitors and explosion mechanisms. Furthermore the discovery of a growing number of exceptionally bright and extremely faint SNe, as well as peculiar events, suggest the existence of an unexpected SN diversity (Benetti et al., 2005), which is difficult to explain within the standard scenarios. With the goal of achieving a better insight into the physics of SN progenitors of all different flavours, we have started the SUDARE programme which is currently running at the VLT Survey Telescope (VST).

Background: SNe as fascinating transients

SNe are energetic explosions related to some of the most important problems of modern astrophysics. They are one of the more promising tools to probe the nature of dark energy in the Universe and provide a natural laboratory for studying the physics of hydrodynamic and nuclear processes under extreme conditions. SNe are involved in the formation of neutron stars, black holes, and gamma-ray bursts and are sources of neutrino emission, high-energy cosmic rays and gravitational waves. The energy release from SNe can trigger episodes of star formation (SF), impacting the evolution of gas flows and contributing to the feedback processes in galaxies. They are also the main producers of heavy elements and are fundamental for modelling the chemical evolution of galaxies and abundance patterns in clusters of galaxies. Moreover, the metal-rich ejecta of SNe are believed to be potentially important sites of cosmic dust formation.

We recognise two physically different classes of SNe: core-collapse induced explosions of short-lived massive stars (CC SNe) and thermonuclear explosions of long-lived low-mass stars (SNe Ia). All stars more massive than about eight solar masses develop an iron core that cannot be supported by any further nuclear fusion reaction, or by electron degenerate pressure, and hence collapse to form a neutron star or a black hole. Different sub-types of CC SNe have been identified on the basis of their spectroscopic and photometric properties (IIP, IIL, IIn, IIb, Ib, Ic; see Turatto et al., 2003). These subtypes have been associated with a possible sequence of progenitor characteristics related to mass-loss history, with the most massive stars and stars in binary systems losing the largest fraction of their initial mass.

Concerning SNe Ia, there is general consensus that they correspond to thermonuclear explosions of a carbon and oxygen white dwarf (WD) which reaches the Chandrasekhar mass due to accretion from a close companion. Two kinds of evolutionary paths for the progenitors are mostly considered in the literature: a) the single degenerate scenario, in which a WD, accreting from a non-degenerate companion (a main sequence star, a red giant or a helium star), grows in mass until it reaches the Chandrasekhar limit; b) the double degenerate scenario, in which a close double WD system merges after orbital shrinkage due to the emission of gravitational waves. If the total mass of the system reaches the Chandrasekhar limit, carbon ignition under degenerate conditions may produce a Type Ia SN explosion.

Motivations: SN progenitors and the nature of SN diversity

The current picture of the death of massive stars is far from clear and several important questions, such as what is the mass range of the progenitor stars of different CC SN sub-types and what are the effects of rotation, metallicity and binary evolution on these mass ranges, still await answers. The simple scheme where only mass loss drives the evolution of massive stars has difficulties in explaining the wide range of properties shown by CC SNe of the same type and the relative frequencies of the different types (IIP 69%, IIb 12%, IIn 9% and IIL 10% of all Type II; Ib 22%, Ic 54% and 24% peculiar events of all Type Ibc; Li et al., 2011).

The direct detection of the SN progenitor on pre-explosion images provides a robust mapping between the progenitor stars and their explosion, but requires high resolution and deep pre-explosion images, so that reliable results are available only for a dozen nearby SNe (Smartt et al., 2009). The nature of the SN Ia progenitor system and the details of the explosion mechanisms are thus still debated.

The use of SNe Ia as standard candles is based on the assumption that all SNe Ia are highly homogeneous (at different cosmic epochs). However, in the last few years spectroscopic and photometric peculiarities have been noted with increasing frequency (about 50 %) and new subclasses of SNe Ia have been introduced (20 % with high expansion velocities, 10 % as SN 1991bg-like objects, 15 % as SN 1991T-like objects, 5 % as 2002cx-like objects; see Li et al., 2011). Whether these subclasses form distinct physical groups from normal SNe Ia, with different progenitors and explosion mechanisms, or whether they lie at the extreme end of a continuous distribution, is still unclear.

In this framework, the relationship between SN properties and the parent stellar populations can help constrain the progenitors and hence deepen understanding of the origin of the diversity. In particular, the simultaneous analysis of the cosmic evolution of SN rates and the dependence of SN rates on some host galaxy properties is a powerful diagnostic tool to investigate the effects of age, environment and metallicity on the SN progenitors and their diversity. For example, it appears that subluminous SNe Ia preferably occur in massive non-star-forming host galaxies, while super-luminous SNe Ia occur in relatively metal-poor host galaxies.

Taking into account the short lifetime of massive stars, the CC SN progenitor scenarios can be probed by comparing the star formation rate (SFR) and the rate of CC SNe in the same galaxy sample, assuming the distribution of the masses with which stars were born, i.e. the initial mass function (Botticella et al., 2012). On the other hand, the SN Ia rate echoes the whole star formation history of the host galaxy due to the time delays between the birth of an SN Ia progenitor and its death. By comparing the observed SN Ia rate in different galaxy types with that expected for the star formation history of the parent galaxy population, it is possible to constrain the distribution of the delay times (Greggio, 2010). In turn, this allows us to test the progenitor scenarios, which predict different fractions of binaries exploding with different delays.

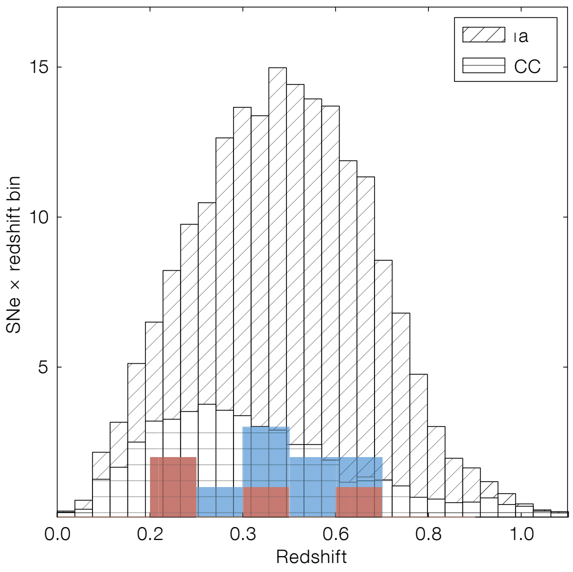

Figure 1. The number of expected SNe discovered by SUDARE in CDFS (200 SNe of which 25 % CC SNe) as a function of redshift. The blue (red) histogram shows the Type Ia SNe (CC SNe) with spectroscopic classification discovered in the first season.

Similar considerations hold for the cosmic SN Ia rate in relation to the cosmic SFR.

A new SN search

Our efforts to investigate the cosmic evolution of SN rates began a decade ago with a SN search exploiting the Wide Field Imager (WFI) at the 2.2-metre MPG/ESO telescope. The Southern inTermediate Redshift ESO Supernova Search (STRESS) discovered 86 SNe (nine SNe Ia and 16 CC SNe with spectroscopic classification) during 16 observing runs distributed over a period of six years (from 1999 to 2005; Cappellaro et al., 2005). We found that the CC SN rate is already higher by a factor of two with respect to the local value by redshift $z = 0.2$, whereas the SN Ia rate remains almost constant. This finding implies that a significant fraction of SN Ia progenitors have a lifetime longer than 2–3 Gyr (Botticella et al., 2008). However, the SN sample collected from STRESS was not large enough to perform a statistically significant investigation of the SN diversity.

Therefore we decided to contribute to the international consortium for the delivery of OmegaCAM and the VST telescope (Capaccioli & Schipani, 2011; Kuijken, 2011). The wide field of view and high spatial resolution of OmegaCAM , jointly with the excellent quality of the VST optics, offers an unprecedented opportunity for an SN search in the redshift range $0.3 < z < 0.6$. This redshift range is crucial to connect measurements from past SN surveys in the nearby Universe and the future high-redshift surveys like the Dark Energy Survey (DES) or, in the longer term, with facilities such as the Large Synoptic Survey Telescope (LSST) and the ESA Euclid satellite mission.

Detailed simulations assuming the VST performance and the observational strategy of SUDARE show that we should discover about 500 SNe, of which 25 % are expected to be CC SNe (Figure 1) by the end of a four-year programme. The size of this SN sample is suitable both for the measurement of the rate of all SN sub-types and to discover rare types of SN explosions. Indeed the depth of SUDARE images allows us to exploit, during each epoch, a volume of space that is about 1000 times larger than that sampled by nearby SN surveys and thus is more suitable to discover rare and peculiar events. Given an observed rate of peculiar SNe of the order of 5 % of "standard" CC and SN Ia rates, we expect, by the end of our programme, to have detected about two dozen of such "weird" stellar explosions.

The novelty of SUDARE is the emphasis that we put on the analysis of the parent stellar population, with the aim of

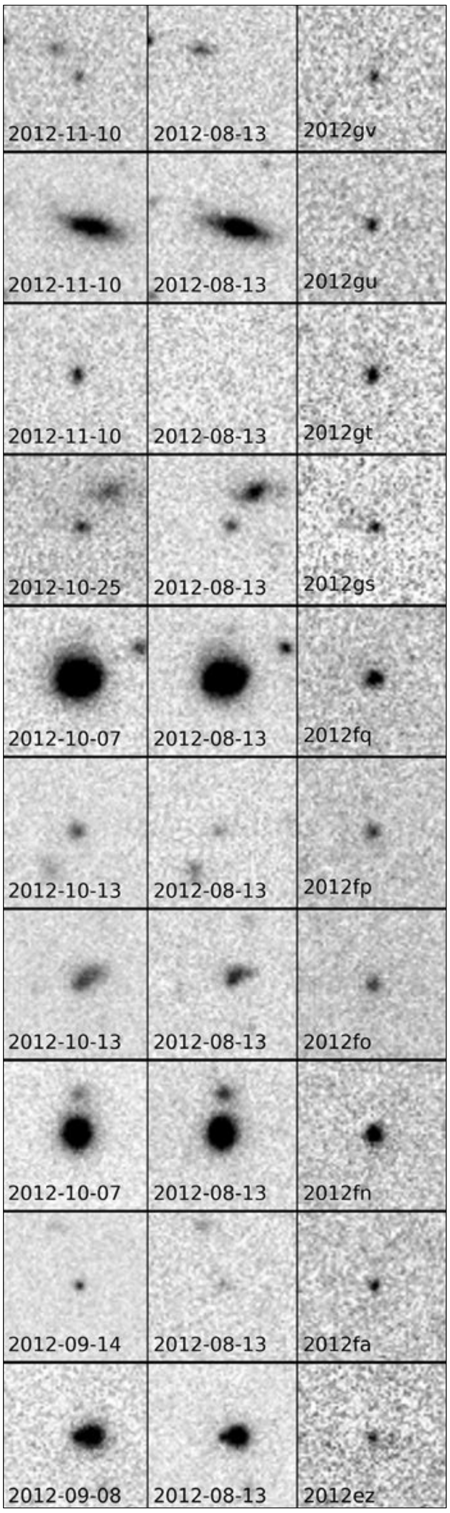

Figure 2. Search image (left panel), template image (centre panel), and difference image (right panel) for the ten SUDARE SNe with spectroscopic classification.

constraining the SN progenitors and investigating a possible evolution of SN diversity with cosmic time. Our goal of measuring SN rates as a function of galaxy age, mass, SFR, metallicity and in different environments requires a detailed characterisation of the galaxy sample surveyed. We therefore decided to search for SNe in two sky fields: the Chandra Deep Field South (CDFS) and the Cosmic Evolution Survey (COSMOS) field. These fields have an extraordinary amount of ancillary data from X-ray to radio wavelengths (e.g., the GALEX Deep Imaging Survey in the ultraviolet, the VISTA–VIDEO ESO public purvey in the near-infrared, the Spitzer–SERVS and Spitzer–SWIRE Surveys in the mid- to far-infrared, the Herschel–HerMES Survey in the far-infrared and submillimetre, and the ATCA–ATLAS Survey in the radio) that will allow us to retrieve important properties of the surveyed galaxies, including redshift, luminosity, morphology, star formation history and mass.

In addition, the VST–Optical Imaging of CDFS and ES1 (VOICE) survey (PIs G. Covone and M. Vaccari) is observing CDFS in the *u*-band and obtaining additional *g*-, *r*- and *i*-band images to improve the accuracy of the photometric redshifts and to estimate galaxy stellar masses, SFRs and environmental properties. The COSMOS field will be also monitored over the next five years in the *Y*-, *J*-, *H*- and *Ks*-bands to unprecedented depth by the UltraVISTA ESO public survey. It will be very interesting to compare the optical and near-infrared SN rates in the same galaxy sample up to redshift 0.3–0.4. This comparison will allow us to estimate the fraction of missed SNe in the optical search due to dust extinction. An important by-product of our search will be the detection of the variability of active galactic nuclei (AGNs) and the gathering of their optical light curves.

Observational strategy

The strategy of the SUDARE survey has been tuned to collect an unbiased and homogeneous sample of all SN types in an unbiased galaxy sample. We are performing a “rolling search”, a frequent, long-term monitoring of the selected sky fields, in the *r*- (with a cadence of 2–4 days), *g*- and *i*-bands (with a cadence of one week) to a limiting magnitude of 25 mag. In order to reduce the possible effects due to cosmic variance, the pointing will change by one degree from season to season so that, by the end of the survey we will have covered two square degrees both for the CDFS and COSMOS fields.

The transients are detected in the *r*-band on difference images obtained by subtracting from a given image a template image acquired at a different epoch (see Figure 2 for some examples). The magnitude limit in the difference image is about 24 mag depending on the quality of the search image and the brightness of the host galaxy in the transient location. Images in *g*- and *i*-bands will provide colour evolution for each transient. A rolling search secures photometric typing for each transient that will be validated by spectroscopic classification for a fraction (30 %) of the SN candidates, obtained through dedicated programmes at 8-metre-class telescopes such as the VLT, Magellan and Gemini South.

A key feature of our strategy is the very rapid turnaround from observation to transient detection. This can be accomplished because of the excellent services offered by ESO, beginning with service observing mode, which is crucial for our programme. This is accompanied by real-time archive ingestion and delivery along with access to a mature tool for VST data reduction (VST-Tube; Grado et al., 2012). As a result we are in the position to obtain spectroscopic classification for transient events within 24 hours of their detection.

The first SNe are coming out ... and it is only the beginning!

SUDARE started on 20 October 2011 and has imaged CDFS in 55 epochs (ESO Periods 88, 89 and 90) exploiting VST and OmegaCAM guaranteed observing time (PI Cappellaro) and imaged the COSMOS field in 30 epochs (ESO Period 88: PI Pignata). So far we

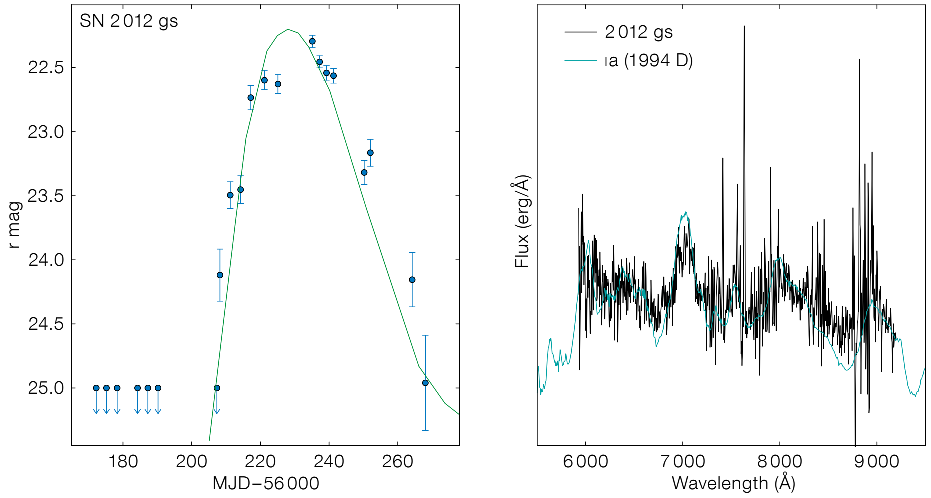

Figure 3. Light curve and spectrum of SN 2012gs, a Type Ia at z = 0.52 discovered by SUDARE. The green spectrum is the best-fit template obtained by GELATO.

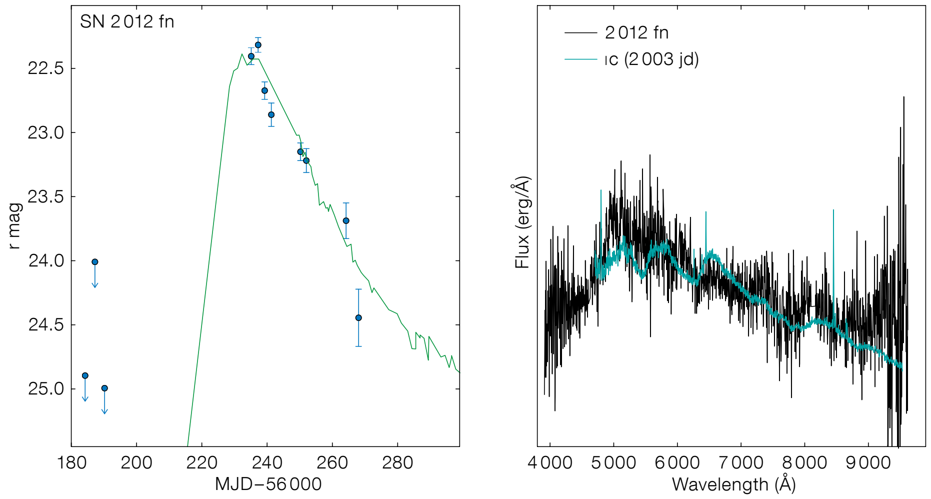

Figure 4. Light curve and spectrum of SN 2012fn, a Type Ic at z = 0.28 discovered by SUDARE. The green spectrum is the best-fit template obtained by GELATO.

have discovered a hundred SN candidates, several variable AGNs and a number of variable stars. In three different nights we obtained spectroscopic classification for a dozen of the SN candidates at the VLT, equipped with the FOcal Reducer and low dispersion Spectrograph and at Gemini-South, equipped with the Gemini Multi-Object Spectrograph. These SNe are reported in the Central Bureau for Astronomical Telegrams (CBET) 3236, 3274, 3311. Six of these SNe are Type Ia with an average redshift of 0.5 (Figure 3 shows the light curve and spectrum of one example, SN 2012gs at z = 0.52), two are Type Ic (Figure 4 shows the light curve and spectrum of SN 2012fn, a Type Ic at z = 0.28) and two are Type II in a redshift range from 0.3 to 0.6. Classifications were performed with the GELATO tool (Harutyunyan et al., 2008).

Four transients were discovered within 0.1 arcseconds from the host galaxy nuclei and all exhibited the spectrum of a Seyfert galaxy. All the SNe were discovered well before maximum light thanks to the temporal cadence of our survey that allows both an early discovery and an optimal photometric coverage. The distribution in redshift, magnitude and SN type of this subsample with spectroscopic classification is in excellent agreement with that expected from our simulations (Figure 1).

The first systematic SN search began about 80 years ago by F. Zwicky at Mount Palomar with a Schmidt telescope (with a field of view of several degrees) equipped with photographic plates. SN candidates were searched for by scanning by eye two overlapped plates acquired on different nights, and over a thousand images were inspected to find only a dozen SNe. In a single image of OmegaCAM with SUDARE, the improved magnitude limit now allows us to detect the same number of SNe. This extraordinary improvement is due to modern CCD mosaic cameras, adaptive optics and the subtraction process of digital images, allowing us to discover faint transients also in distant galaxies. The authors of this paper consider it a privilege to have started an SN search in 2011 and they all agree that the acronym SUDARE (in Italian this word means "to exude sweat") would have been more appropriate for Zwicky's survey.

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