Chapter 39
Supernovae as Cosmological Probes

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Abstract I review the use of SN Ia as distance indicators for measuring H_0, the Hubble constant, and the expansion history of the Universe. Most current estimates of H_0 are in the range 74–76 $\mathrm{km\,s^{-1}Mpc^{-1}}$, in significant disagreement with the PLANCK's CMB estimate that is 10 % smaller. The main issues for SN Ia calibration, namely the luminosity vs. light curve shape relation and the correction for dust extinction are briefly addressed. SN Ia have been the key for the discovery of the acceleration of the cosmic expansion and in the near future they are expected to give a significant contribution to reveal the nature of dark energy.

39.1 Introduction

The link of supernovae with cosmology began with their distinction from ordinary novae in the context of the *Great Debate* on the nature of *nebulae* that, a century ago, marked the beginning of modern cosmology [43]. It was argued that if the *island nebulae* were extra-galactic, the novae that they were hosting would have an "impossibly great absolute magnitude", far more luminous than ordinary Galactic novae [11, 39]. On the other hand, there was evidence for a significant dispersion of the magnitudes of galactic novae that prompted for the separation into a lower and an upper class, the latter reaching an absolute magnitude similar to that of the system where they appear [21]. After the determination of the actual scale of the Universe, the upper class novae were labelled supernovae (SNe) with the suggestion that they were related to the formation of neutron stars [5].

Hereafter, SNe have become important as tracers of the galaxy stellar population and of the cosmic star formation rates (see Botticella et al., this volume) and as counterparts of enigmatic high energy events, i.e. cosmic rays, gamma-ray bursts

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and gravitational waves (Grado et al., this volume). More important, SNe have consolidated their role of accurate cosmological probes for the measurement of the Hubble constant and of the cosmic expansion history. In the following I will briefly review the contribution of SNe in this field and the prospects for future experiments.

39.2 SNe and the Hubble Constant

The history of the Hubble constant determination is shown in an instructive plot by Huchra [19]. The early measurements were affected by severe underestimation of the nebulae distances that it took some time to sort out until, in the early 1970s, the estimates of H_0 appeared to converge. However, at this point a controversy began that lasted over two decades between different groups that, while progressively reducing their error-bars, were claiming incompatible values at the extremes of the range 50–100 $\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (in the following H_0 units are omitted). The first attempts to use SN Ia to measure the Hubble constant did not solve the controversy [12, 35] as shown in Fig. 39.1. An exception was the result of Capaccioli et al. [9] that, by combining novae and SN Ia, derived the relative distance of Virgo and Coma clusters and a value of $\mathrm{H_0} = 70 \pm 15$. In fact, this value is very close to those obtained in the last decade using Cepheid's calibrated SN Ia [3, 15]. The most recent analysis appear to converge to $\mathrm{H_0}$ values between 74–76 with errors $<5\,\%$ [14, 16, 33, 40]. We note however that there is a group still arguing for a smaller value, $\mathrm{H_0} = 63.7 \pm 2.3$ [37, 42] that, given the small errors, is incompatible with the above estimates.

The apparent comforting convergence of (most) $\mathrm{H_0}$ measurements was perturbed by the publication of the cosmological parameters derived from the CMB observations by Planck. The temperature and lensing data interpreted with a six-parameter inflationary ΛCDM cosmology give $\mathrm{H_0} = 67.8 \pm 0.9$ [31]. Although formally this value sits in between the SN Ia measurements listed above, most researchers

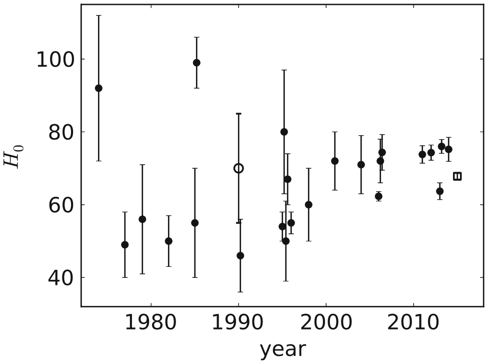

Fig. 39.1 The history of H_0 measurements through SNe. The *open circle* is the Capaccioli et al. [9] estimate discussed in the text. The *open square* is the estimate obtained from the analysis of the CMB map obtained by the Planck satellite [31]

would agree that there is a real tension between Planck and SN Ia estimates. This is an important issue because as stressed by the Planck collaboration [31] if this is confirmed it will be strong evidence for additional physics beyond the base ΛCDM model.

39.3 SN Ia Calibration Issues

The use of SN Ia as distance indicators requires accurate calibration and correction for dust extinction. Until the early 1990s SN Ia were considered standard candles with a very low dispersion of the absolute magnitude at maximum ($\sim$0.2 mag) mainly attributed to observational errors rather than to intrinsic differences [36]. Actually, it was soon obvious that there is some diversity in light curve evolutions with *fast* and *slow* events, although at the beginning no evidence was found for a difference in absolute magnitudes between the two sub-types [6]. Eventually, the improved photometry obtained with CCD detectors revealed the existence of a correlation between light curve shape and absolute magnitude, with slow declining objects being more luminous [18, 29]. This correlation, now a fundamental tool for the accurate calibration of SN Ia, has been related to variation of the mass of ^{56}Ni produced in the explosion. However, the residual scatter around the relation appears to be intrinsic and pointing to a second parameter [7] possibly related to asymmetries in the explosion along with varying viewing angles for different events [22].

A key issue for SN calibration is the correction for dust extinction that is typically derived from the color excess measured after assuming that SN Ia have all similar intrinsic color [30]. The color excess is converted into an absorption estimate by means of the relation $A_V = R_V \times E(B - V)$. A surprising finding was that the dispersion of the SN Ia absolute magnitudes is minimized by adopting a value of R_V that is significantly smaller than the standard reference value of 3.1 [9]. This result has been confirmed in all recent studies based on similar statistical arguments [3, 8, 20] but also on detailed analysis of single events [4, 13] that return $R_V \simeq 1.4$–1.8. Whether this effect is due to peculiar properties of the dust around SN Ia or is a consequence of multiple scattering in dense clouds is still unclear [24, 45].

39.4 SNe and the Acceleration of Cosmic Expansion

The first attempt, in the mid 1970s, to use SNe to test cosmic expansion was defeated by large errors of the photometry and poor SN calibration [34]. At that time, the paradigm was that by measuring the deceleration parameter it was possible to obtain an estimate of the matter density in the Universe. Measuring cosmological distances appeared to require a new generation of telescopes/instruments and in particular, a project under study at that time, a Space Telescope [10, 44]. Actually, the advancement of CCD detectors allowed to start paving the road already using ground based telescopes: the first distant SN, at $z = 0.31$, was found with the Danish 1.5 m telescope in 1989 [23] followed in 1992 by a SN Ia at $z = 0.46$ found with the INT 2.5 m telescope [26]. From here on the work of two groups, the SN Cosmology Project (SCP[1]) and the High-z team[2] and, finally, the overwhelming power of HST, made the progresses very rapid. Early reports, based on small SN samples, were cautious [17, 27] but eventually the two competing groups almost simultaneously announced the same surprising result: the Universe expansion was accelerated [28, 32, 38]. This results properly complemented by CMB measurements, that constrain the Universe to a flat curvature, required the presence of a dominant cosmological constant or of some sort of dark energy. The analysis of the latest SN data, a combination of local SN Ia, Sloan Digital Sky Survey for low redshift, Supernova Legacy Survey for intermediate redshifts and HST for high redshift, confirms that for a flat Universe $\Omega_M = 0.27$, hence $\Omega_\Lambda = 0.73$, with an error of only 5 % [41].

The discovery of the acceleration of the Universe, that led to the Nobel Prize in Physics in 2011, immediately raised a new question: what is the nature of the mysterious *dark energy* ?

Answering this question requires an accurate measurement of w, the ratio of pressure to energy density for this component, i.e. the equation of state of dark energy. In particular, considering that in general w may not be constant, the equation of state is parametrized as $w(a) = w_0 + (1-a)w_a$ where a is the scale factor, w_0 the present value and w_a its rate of change. A conventional estimate of the ability of a given experiment, or combination of experiments, to measure the equation of state is the figure of merite defined as $FoM = 1/\sigma(w_0)\sigma(w_a)$ [1].

Current estimates using combination of SNe and CMB measurements indicate that $w_0 \sim 1$ with no evidence for a dynamical dark energy, i.e. w_a consistent with 0, though the errors are still fairly large, with $FoM \sim 10$ [41].

The goal of future experiments is to measure all cosmological parameters with an accuracy that is one order of magnitude better than those available today. A detailed analysis has shown that this requires the combination of all four principal techniques, namely baryon acoustic oscillations, galaxy clustering, weak lensing and SNe and, for all probes, improving significantly statistical and systematic uncertainties [1, 25]. For SNe, this means to increase the number of high redshift

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[1] http://supernova.lbl.gov

[2] https://www.cfa.harvard.edu/supernova/HighZ.html

SN Ia with good photometry from hundreds to thousands. For systematic errors the emphasis is in cross-band calibration because typically nearby and distant SNe are observed in different bands. We also need to constrain the possible evolution of SN Ia properties, that requires both empirical tests but also improvements of our understanding of SN Ia physics.

39.5 On-Going and Future SN Surveys

A running project that is aimed to make a significant progress in this field is the Dark Energy Survey[3] (DES). This project consists in a wide area survey using the 3 deg^2 DECam instrument installed at the 4 m Blanco telescope at CTIO. DES will exploit the different techniques mentioned above; for SNe it features a 30 deg^2 time-domain survey that is expected to produce few thousand SN Ia up to $z = 1$. The redshift limit is set by the fact that, at higher redshifts, the bulk of SN emission moves in the near-infrared (IR). In fact, to obtain a large sample of SN Ia at $z > 1$ requires an IR, wide field imager in space. A unique opportunity in this respect is offered by EUCLID,[4] the ESA medium size mission that is planned to flight in the early 2020s. The main tools of EUCLID are weak lensing and baryonic acoustic oscillations that will be addressed by mean of a combined optical/near-infrared survey of 15,000 deg^2. In addition, it was argued that by using 6 months of the EUCLID time we can obtain a sample of 1,700 SN Ia in the redshift range $0.75 < z < 1.55$ that, combined with a LSST sample (see next), can give a $FoM \sim 200$, from SNe only [2]. The decision about the actual implementation of a SN survey in EUCLID is still pending.

LSST[5] is a 8.4 m telescope that is expected to perform a wide-field astronomical survey of over 20,000 deg^2. Each patch of sky will be visited about 1,000 times in 10 years. In the standard operating mode, providing frequent all-sky coverage, LSST is expected to discover roughly 250,000 SNe per year, with SN Ia at a mean redshift of about 0.45. SNe will be discovered also from a "staring mode" search of a more limited area of sky. After 10 years and 10 min per night spent staring at a single field will yield 14,000 SNe with a mean redshift of 0.75.

Finally, the Wide-Field Infrared Survey Telescope (WFIRST[6]), a NASA space observatory, is planned to perform wide-field imaging and slitless spectroscopic surveys in the near-IR. The current design of the mission (named AFTA) makes use of an existing 2.4 m telescope. For SNe the baseline is to perform a multi-tier survey scanning different sky areas with progressively deeper limits that is expected to produce 2,500 SN Ia up to $z \sim 1.7$.

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[3] http://www.darkenergysurvey.org

[4] http://sci.esa.int/euclid

[5] http://www.lsst.org/lsst/

[6] http://wfirst.gsfc.nasa.gov

Therefore, the prospects are that in the next two decades SN Ia will maintain a key role as cosmological probes and they will give a major contribution to address the nature of dark energy.

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