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Cosmology with Type Ia supernovae

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In this short review, some key aspects of the cosmology with type Ia supernovae are discussed in light of the recent results of high redshift surveys. The interpretation of SNe colours, the impact of calibration and the recent developments in the tests for an evolution of the population with redshift are addressed.

1 Introduction

Since 1998 (Riess *et al.*[1], Perlmutter *et al.*[2]), surveys of cosmologically distant Type Ia supernovae (SNe Ia) have indicated an acceleration of the expansion of the Universe, distant SNe Ia being dimmer that expected in a decelerating Universe. With the assumption that the Universe can be described on average as isotropic and homogeneous, this acceleration implies either the existence of a fluid with negative pressure usually called "Dark Energy", a constant in the equations of general relativity or modifications of gravity on cosmological scales.

Whereas other cosmological probes comfort this result when combined (cosmic microwave background[3] and baryon acoustic oscillations[4]), SNe Ia observations remain today mandatory to study Dark Energy or its alternatives, in the sense that they directly give us the history of the expansion of the Universe up to redshifts of the order of one.

With the statistics of current and future supernovae surveys, systematic uncertainties dominate the error budget on cosmological parameters. However, most systematic uncertainties can be reduced with the data themself and as a consequence follow the statistics as we will illustrate in this review. Those systematic uncertainties can be broadly classified in two classes, one related to the measurement of SNe Ia parameters that can be converted into distance estimators, and one related to the subsequent use of those SNe Ia parameters for cosmology. In the first class enter photometry, calibration, and light curve fitting issues, whereas the second class concerns astrophysical uncertainties: the potential evolution of the population with redshift, contamination by core collapse supernovae, extinction and gravitational magnification along the line of sight and the impact of peculiar velocities.

As we cannot detail all those issues in this short review, we will focus on some aspects of the light curve fitting techniques used, and some key systematic uncertainties that limit today the statistical strength of SNe Ia to constrain cosmological models.

2 Type Ia supernovae as standard candles

A SN Ia is a very bright explosion of a star (10^{10} solar luminosities) with a duration of order of a month. It is primarily identified by its spectrum about maximum luminosity which presents broad absorption features from the ejected material at speeds of order of 20000 km.s^{-1}. The particularity of a SN Ia with respect to the other classes of SNe is this absence of hydrogen lines and the presence of silicon. From those observations, it is very likely that the progenitors of those SNe Ia are white dwarfs fed by a companion star in a close binary system, exploding when their mass reaches the Chandrasekhar limit. However the detailed scenario is poorly known. For instance we do not know yet the precise nature of the companion, whether it is another white dwarf or a giant star (see for instance Hillebrandt & Niemeyer[5] for a review). The maximum luminosity of a SN Ia is correlated to the width of the light curve (first measured in Johnson B-band (M. M. Phillips[6]) and then extended to other bands) and the SN colour as measured by the difference of magnitudes (or ratio of fluxes) in B and V bands. Once corrected for those correlations, the absolute maximum luminosity has a dispersion of order of 15% which make SNe Ia a fantastic tool to measure distances with a precision of order of 8% on cosmological scales.

Practically, we define a distance modulus μ as the rest-frame B-band magnitude (m_B^*) of the SN minus its absolute magnitude, with linear corrections as a function of a shape parameter (for instance a stretch factor s or its alternatives), and a rest-frame colour (c).

$$\mu = m_B^* - M_B + \alpha(s-1) - \beta c \tag{1}$$

It is compared to $5\log_{10}(d_L(\theta,z)/10\ \mathrm{pc})$ where $d_L(\theta,z)$ is the expected luminosity distance at redshift z for a cosmological model with parameters θ. All recent high-redshift cosmology analyses use those parameters (m_B^*, s, c) in a more or less obvious way (Riess *et al*[7,8], Astier *et al*[9], Wood-Vasey *et al*[10]) with the notable exception of the CMAGIC technique which relies on a colour-magnitude diagram of SNe Ia (Wang *et al*[11], Conley *et al*[12]). The challenge of a cosmology application is to derive them with a minimal redshift dependent bias. Also, the determination of those parameters, their interpretation and subsequent usage to derive distance estimates vary significantly among authors. We will address those issues later.

No other parameter derived from the observed light curves of SNe Ia that correlate with luminosity has been found so far. However, several indicators based on the equivalent width of spectral features present promising correlations with luminosity (Nugent *et al*[13]). They provide a new approach that may help to robustify the purely photometric distance estimates used so far. Still, a much higher signal is required for those spectroscopic indicators so that they cannot be used at the highest redshifts.

3 Light curve fitting

3.1 An empirical modeling

The goal is to evaluate for each SN a set of redshift-independent parameters from observations performed with a limited set of filters, with a limited cadence of observations. This requires a model of the spectral sequence of the SN in order to interpolate among observations.

Despite the fact that the physics involved in the explosion mechanism is rather well known, it is extremely difficult today to make quantitative predictions for the observed signal based on a physical model. Indeed extremely precise 3D modeling is required in order to simulate the flame propagation in the SN progenitor. As a consequence, an empirical modeling of the observables is needed. Historically, light curve templates were built in pre-definite filters from a sample of nearby SNe (see for instance Goldhaber *et al*[14]). This required a correction of the observations for redshifted supernovae, usually called k-correction (Nugent *et al*[15]). Those were performed using an average spectral sequence based on a set of spectra obtained at different epochs (days after maximum light) of the SN. This method is applied for the MLCS2k2 light curve fitter (Jha *et al*[16]), with tabulated k-corrections as a function of epoch, redshift and colour.

More recently, techniques based on an explicit modeling of the spectral sequence have been developed. The data are not corrected but directly compared to the integral of the spectra in a model of the instrumental response (SALT(2): Guy *et al*[17,18], SIFTO: Conley *et al*[19]). The advantage is to keep track of the correlations between the light curve shape, colours and the spectral properties in the fitting process.

3.2 Impact of a limited training sample : using high-z SNe

This light curve fitting technique is the fundamental ingredient of the cosmology analysis. Especially, the assumed broad-band colour relations in the wavelength range of the model have a direct impact on the derived distances. In order to illustrate this, let us consider two SNe observed in R and I band at redshifts of 0.5 and 0.8. Since those R and I observations correspond to the rest-frame B,V and U,B bands respectively, the ratio of distances derived for those two SNe is directly proportional to the $(U-B)-(B-V)$ colour of the model. Since all light curve models are empirically derived from a limited training set, this latter colour has an uncertainty which introduces a redshift-dependent correlation among the derived supernovae distances.

Today, more than ten times as many SNe have been observed at high-redshift ($z >$ 0.4, in surveys such as ESSENCE[10] and SNLS[9]) than at low redshift ($z < 0.1$). We will probably still have more high-z SNe in the future despite the upcoming data from nearby SNe programs such as SNFactory, KAIT, Carnegie, CFA and SkyMapper (new high-z surveys will also start soon, e.g. PannStarrs, the Dark Energy Survey and LSST on a longer term basis). As a consequence, high-z SNe must be considered in the training of the light curve models in order to beat the statistical limitation of the nearby sample. This has been done with the SALT2 and SIFTO models, it probably requires some adjustments in the MLCS2k2 technique which makes use of the SN distance in the training process.

3.3 Modeling of the near UV emission

High-z SNe permit the observation of the rest-frame near UV emission from the ground without the need of space telescopes. Near UV is modeled in SALT2 and SIFTO using SNLS photometry of SNe in g' and r' bands up to a redshift of 1, with complementary spectroscopic observations obtained at VLT, Gemini and Keck (Balland *et al*[20], Howell *et al*[21], Ellis *et al*[22]). Using near UV data allows for a drastic improvement of the colour and hence distance estimate for SNe at redshifts of order of 1, where the sensitivity of the rest-frame B and V is limited by the quantum efficiency drop of CCDs in the near infrared. However, we still lack spectroscopic observations at early and late epochs (the primary goal of the SNLS spectroscopic program was to provide a identification of the SNe which is easier at maximum luminosity).

3.4 Diversity of SNe Ia colours : intrinsic variation or absorption by dust?

There is still a lot of debate today about the treatment of the SN $B-V$ colour. Whereas all cosmology analyses based on SNe perform a linear correction of distances with the measured colour, the value of the coefficient used and its interpretation differ significant from one analysis to another. In the SNLS collaboration[9] this coefficient β is marginalized over in the cosmology fit, without any attempt to separate the reddening effect of dust absorption or an intrinsic variation. On the contrary, the MLCS2k2 technique used in ESSENCE[10] and GOODS[7,8] surveys considers that the derived $(B-V)$ colour offset comes from extinction by dust, and therefore that the β correction should be identified with the R_B value of the Cardelli *et al*[23] extinction law. Whereas $\beta \simeq 2$ from the cosmology fit of SNLS data, a value of $R_B = 4.1$ is considered in the other analyses. This difference merits some attention.

As first noticed by Tripp[24] in 1998, when the $(B-V)$ colour at maximum light is obtained from a simple stretched light curve template fit on nearby SNe, the residuals to the Hubble law do correlate with colour with a slope $\beta \simeq 2$. In the fitters as designed in SALT(2) and SIFTO, we naturally obtain the same result because the basic ingredients are the same (except for the use of a more elaborated treatment of the variation of shape of light curves and k-corrections). Recently, Conley *et al*[25] have shown that either we live at the center of an under-dense region of the Universe as claimed by Jha *et al*[16], or the relation between SN colours and luminosity does not follow the one expected for the Galactic extinction and $\beta \simeq 2$.

This low value of β points to either a very unusual extinction law in host galaxies of SNe Ia or an intrinsic colour variation that dominates the effect of extinction. There are hints for that hypothesis. First, the distribution of SNe colours observed in SNLS in passive elliptical galaxies is similar to that of SNe in active galaxies, despite the fact that we expect a much smaller dust content in the former. Second, the colour variation law (which describes how the SN flux varies with colour as a function of wavelength) can be derived from the SN data themself, and it differs significantly from the Cardelli *et al* extinction law in the near UV and U-band, even for extreme value of R_B (see Guy*et al*[17,18]). In SIFTO[19], the derived relation between the $(U-B)$ and $(B-V)$ colours of SNe can not be explained with an extinction law either.

While there is not yet a definitive proof that the colour we observe is intrinsic to the SN, we still have to relax the assumption that it is purely due to dust extinction as modeled by Cardelli *et al.* This has some consequences on the cosmology analysis. First, in any survey, the colour distribution of SNe varies with redshift because of Malmquist bias (bluer SNe are brighter and hence dominant at the detection limit of a survey). Applying a wrong correction to luminosity introduces a redshift dependent bias. This occurs at the highest redshift of all surveys but also for nearby SNe that were observed by other means (this is the effect at play in the Hubble Bubble detection claim[25]). Second, assuming that the observed colours are purely due dust has led some authors[7,8,10] to use priors on its distribution.

To conclude on this section, several groups have embarked on sophisticated methods to estimate distances from light curves fits. Those methods are purely empirical. Whereas implementation varies, the basis ingredients are the same (rest-frame B-band magnitude, a colour, a shape parameter). Important differences remain on the treatment of colours.

4 Systematic uncertainties

The cosmological constraints obtained with the current high redshift SNe Ia surveys now have a systematic uncertainty budget of the same order as the statistical one. For the measurement of a constant equation of state parameter w of Dark Energy in a spatially flat cosmology, Astier *et al*[9] and Wood-Vasey *et al*[10] obtained $w = -1.023 \pm 0.090(\mathrm{stat}) \pm 0.054(\mathrm{syst})$ and $\Omega_M = -1.05 \pm 0.13(\mathrm{stat}) \pm 0.13(\mathrm{syst})$ with respectively 71 and 60 high-z SNe. Those on-going SNLS and ESSENCE surveys, with the addition of the SDSS, one will publish soon results with several hundreds of high-z SNe Ia. On a long-term basis, the LSST project will derive cosmological constraints from more than 10^5 SNe Ia[26].

Those uncertainties are specific to the usage of standard candles as a cosmological distance probe, namely the measurement of redshift-corrected flux over orders of magnitude from a redshift of 0 to 1. A first class of systematics have to do with detection bias, photometry, calibration and k-corrections, the other one is related to the evolution with redshift of the SN population and the effect of foreground absorption (host galaxy or inter-galactic dust) or dispersion (magnification by mass lumps) in the line of sight.

In order to illustrate some of those systematics, let us consider two SNe at redshifts $z_1 = 0$ and $z_2 = 0.5$, observed in B and R-band respectively, so that those observations correspond roughly to the same rest-frame wavelength range. The ratio of luminosity distance is related to the observables by the following formula.

$$\left(\frac{d_L(z_2=0.5)}{d_L(z_1=0)}\right)^2 = 10^{-0.4\,[m_2(R)-m_1(B)]} \quad (2)$$

$$\times \frac{\int \phi_{SN}(\lambda) B(\lambda(1+z_1)) d\lambda}{\int \phi_{SN}(\lambda) R(\lambda(1+z_2)) d\lambda} \quad (3)$$

$$\times 10^{0.4\,[m_{ref}(R)-m_{ref}(B)]} \times \frac{\int \phi_{ref}(\lambda) R(\lambda) d\lambda}{\int \phi_{ref}(\lambda) B(\lambda) d\lambda} \quad (4)$$

Observed magnitudes (2) have to be redshift-corrected as if observed in the same filter (3), and in order to interpret those in term of fluxes, we must know the magnitudes and spectral energy density of a reference star (4).

We have already illustrated the potential issues with k-corrections. Photometry can be controlled with simulations (fake SNe in the images), it is not a limiting factor. The calibration is more difficult.

4.1 Calibration

The trivial role of calibration is to transform the observed counts in the detector in physical flux units. SNe observations in the redshift range from 0.01 to 1 have to be cross calibrated over four orders of magnitude, with a relative precision of order of 0.01 mag today and even much lower in the future with surveys like SNAP/JDEM or LSST. In addition, those observations are performed in very different optical bands, from 400 to 800 nm. Hence, not only do we have to relate high-redshift observations to a same magnitude system as nearby ones to ensure that we are at the same scale, but also we have to find a means to interpret those measurements in different bands in term of energy flux ratio as dictated by the luminosity distance definition.

As done traditionally in astronomy, SNe observations are combined with field stars observations the flux measurements of which in turn are compared to those of secondary standard stars, that are part of larger photometric catalogs used by the community. This first step requires a good uniformity correction of the camera response (see e.g. Regnault et al [27]). It becomes a difficult task when the secondary stars were observed with a very different filter set as the one used in the SNe survey. This is for instance the case in SNLS where Megacam is equipped with SDSS-like filters (g',r',i',z') whereas the secondary catalog developed over years by A. Landolt [28,29,30,31] was obtained with U,B,V,R,I filters like the original catalogs of Johnson and Cousins. An ideal calibration would require to know the spectrum of each of those stars. This information missing, we must rely on colour transformations controlled by synthetic photometry based on spectro-photometric catalogs. The situation will improve in the near future with the calibration of on-going surveys on the SDSS southern-strip catalog [34].

Once field stars are put in the same magnitude system, we still have to transform them into fluxes. In the particular case of the Landolt system, the most direct path is through the recently published observations by Landolt and Uomoto [32] of spectrophotometric stars observed by HST that are calibrated against white dwarf models [33]. This step is not free of systematics.

We cannot reasonably hope today for a better calibration than 0.01 mag in the flux ratios of the B and R band, which translates into a systematic uncertainty of the same magnitude in the relative distance moduli of SNe at $z = 0$ and 0.5. Since the standard deviation of SNe about the Hubble line is of 0.15 mag, this former number has the same weight in the cosmological constraints as 225 SNe, a number that will be reached in the SNLS survey. As a consequence, any forth-coming supernova survey will need a large calibration effort to improve constraints on cosmological parameters. When doing so, the cosmological value of the current and past surveys will also improve. R&D studies have started to explore an independent calibration path through the in situ calibration of ground based telescopes with dedicated illumination systems (see e.g.

Brown *et al*[35] at CTIO and Juramy *et al*[37] at CFHT). Of course an additional monitoring of the atmospheric transmission is needed, studies for Pan-Starrs and LSST are also developed[36].

4.2 Evolution of the SN Ia population

Evolution of the SN Ia population is the most immediate worry for their usage as standard candles. From the observational point of view, one can either compare SNe properties as a function of redshift, or study their correlation with the environment, i.e. the host galaxy properties : morphology, age, star formation rate and metallicity. Indeed any evolution scenario is related to the properties of the environment during the lifetime of the SN progenitor.

In Astier *et al*[9], it was found that there is no indication for an evolution with redshift of the distributions of light curve shape, SN colour and their correlation with luminosity, once the selection effects are accounted for. A somehow different conclusion is obtained by Howell *et al*[38] who found an increase of the average light curve width with redshift (though without any impact on distance estimate when the luminosity–width correlation is accounted for); this result however relies on very distant SNe observed by Riess *et al*[7,8], with the hypothesis that those observations do not suffer from Malmquist bias.

Alternatively, a lot of effort has been put into detailed comparisons of spectroscopic indicators (equivalent width, ejecta velocities) at low and high redshifts (see Balland *et al*[39], Blondin *et al*[40] and Bronder *et al*[41]). No significant deviation between the two populations has been found so far. However, due to the requirement of a much higher broad-band signal to noise ratio for spectroscopy than for photometry, those studies do not reach the statistical accuracy needed to bring strong constraints on evolution.

The most powerful test of evolution is based on the comparison of SNe photometric properties as a function of their host galaxy. It has been found that the distribution of width of SNe light curves was correlated with the host galaxy morphology (see Hamuy *et al*[42,43,44], Riess *et al*[45], Gallagher *et al*[46]). This has been confirmed with SNLS data at high redshift using stellar evolutionary models fitted on the observed colours of the galaxies (Sullivan *et al*[47]). SNe Ia exploding in passive environments have a lower stretch (light curve width) than in active star forming galaxies. Hence the SNe properties do depend on their environment. However, when corrected for the brightness – width relation, the absolute magnitudes of SNe are alike. More alarming is the recent claim from Gallagher *et al*[48] that residuals to the Hubble diagram are correlated to the host-galaxy metal abundance as predicted by a theoretical model (Timmes, Brown & Truran[49]) although with a different correlation factor. This result definitely needs confirmation with a larger SNe sample.

If evolution can indeed be fully tested with the comparison of SNe in different types of host galaxies, the associated uncertainties will decrease as the SNe sample increases, and hence those uncertainties should not be called systematic. As an example, one can associate to each class of host galaxy a set of parameters (M_B, α and β) or a continuous alternative as a function of specific star formation rate or metallicity indicators. With such a procedure, our lack of knowledge on the detailed impact of the environment can be propagated to the statistical uncertainties on cosmological parameters, through the marginalization of those additional parameters in the fit of the Hubble diagram.

4.3 Extra-galactic line of sight

Magnification of the SNe signal from gravitational lensing due the presence of Dark Matter halos along the line of sight has a very small impact in current surveys but might be an issue for a space mission such as JDEM which targets higher redshifts (see Bergström *et al*[50], Holz & Linder[51]). With flux conservation, most SNe are demagnified and few of them significantly magnified, hence bright outliers should probably not be discarded. More interesting is the possibility to measure the mass of the galaxies embedded in Dark Matter halos as a function of the stellar luminosity and other galactic properties. J. Jonsson *et al* have shown that a signal could already be detected in current high redshift surveys.

It is unlikely that gray dust is responsible for the observed dimming of SNe with redshift within an Einstein-de Sitter Universe, but some extinction is not excluded. Stringent constraints have been provided by Östman & Mörstell[53] from the distribution of colours of a large sample of quasars; those constraints are of course a function of the assumed extinction law of the intergalactic dust.

4.4 Propagation of systematic uncertainties

All calibration uncertainties, Malmquist bias uncertainties, along with the statistical uncertainties of the light curve fitters (which include the uncertainties on the colour or extinction law) introduce correlated redshift-dependent uncertainties in the distances of SNe. Whereas systematics are often quoted in the final results for benchmark cosmology models, they are not accounted for in the confidence levels, and the resulting covariance matrix of distances is not published. The consequence is that most subsequent use of the SNe Ia data samples simply ignore systematic uncertainties, which might be a problem for tests of non-standard cosmological models or combinations with other cosmology probes. A first attempt to account for this is proposed by Kowalski *et al*[54].

5 Conclusion

Large on-going high-z supernovae surveys (SNLS, ESSENCE, SDSS) are now producing results where systematic uncertainties are becoming dominant. With the short and longer term projects such as Pan-Starrs, DES, LSST, JDEM, which will detect and follow-up many more SNe Ia, those systematics will be a major aspect of the analysis. Fortunately all of them can be reduced. The SN modeling accuracy can follow the statistics of high-z SNe once they are included in the model training. The potential evolution of SNe can be controlled when the host galaxy properties are accounted for in the distance estimate. The challenge of future surveys will probably be the calibration. A significant improvement is required to reach the full statistical potential of SNe. The development of calibration devices on large telescope is essential for this science, provided we can also monitor the atmospheric transmission with sufficient accuracy.

On a short term basis, low-z SNe in the Hubble flow are missing in term of statistics and all cosmology results based on SNe Ia share almost the same low-z sample. There are also potential systematic issues in this sample: it is virtually impossible to model the selection bias of this heterogeneous sample, and the calibration that have been done is probably not precise enough for the level of accuracy that is necessary today.

From the SN phenomenology point of view, the unfolding of the effect of intrinsic colour variation and dust extinction reddening are needed for a better treatment of selection effects and dust evolution.

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