HIGH REDSHIFT SUPERNOVAE: COSMOLOGICAL IMPLICATIONS

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Abstract

We review the findings for the values of the cosmological parameters as derived from high-redshift SNIa measurements. The most recent results confirm the picture of a non-empty inflationary Universe that is consistent with a cosmological constant $\Omega_\Lambda \simeq 0.7$. This implies that the expansion of the Universe is currently accelerated by the action of some mysterious dark energy. We also discuss the possibility and the consequences of the fact that SNIa may not be perfect standard candles, in the sense of having properties in the early Universe that are systematically different from those they have at the present times.

1 Introduction

In the early part of this century, the pioneering work by Hubble, who first observed that galaxies were receding from each other and concluded that the Universe had to be expanding, led to a revolution in our fundamental understanding of the Universe. In the 1960’s, the discovery of the Cosmic Background Radiation provided a physical foundation for the expanding Universe. In the 1970’s and 1980’s, the emerging model, i.e., the hot Big-Bang became well established.
Currently, a large number of fundamental physical and astrophysical observations and theories are providing the foundation and tests for the hot Big-Bang model. In order to compare models with observations meaningfully, one needs accurate and reliable values of important cosmological parameters. With this motivation, special efforts have been made in the course of the years in this direction and recently enormous progress has been made to measure $H_0$ and the deceleration parameters with small errors.

To carry-out these measurements, one needs distance indicators whose intrinsic brightness is sufficiently well known and which are bright enough to be seen at cosmologically significant recession velocities i.e., well away (far enough) from any local velocity perturbation. Since supernovae are very bright objects and are relatively common (in an “average cluster of galaxies” with, say, $10^{13} \, M_\odot$ in stars, one may expect several SN explosions to occur per year), they constitute prime candidates to probe distances to galaxies.

2 Supernovae of Type Ia and the Expansion of the Universe

Supernovae of a particular type, denoted as Type Ia supernovae (SNIa) and characterized by the absence of hydrogen in their envelopes, are perhaps the best “standard candles”: they are so similar to each other that their brightness provides a dependable gauge of their distance, and so bright that they are visible billions of light years away. However, knowing that they are all alike is not enough, one needs also to determine the exact value of their luminosity before using them as proper standard candles. That SNIa could be used as standard candles has been proposed for many years (e.g., Kowal 1968). However, most of the progress in this field has occurred over the last decade.

Extensive ground-based surveys have identified a large number of new supernovae and characterized their global properties in a statistically meaningful way. At the same time, using the Hubble Space Telescope, an international team led by Allan Sandage, and including Gustav Tamman, Abi Saha, Duccio Macchetto and the author, has carried out an extensive program to determine the absolute brightness of a selected sample of supernovae. This has allowed to place SNIa on an absolute scale and the expansion rate of the Universe, the so-called Hubble constant to be determined with a precision of 10%. The derived value for the Hubble constant
Figure 1: The Hubble diagram based on: left hand panel - Cepheids (large dots), TF distances (small dots), and galaxy groups/clusters (squares); right hand panel - SNIa calibrated distances (Tammann et al. 2002).

is $H_0 = 59 \pm 6 \text{ km s}^{-1} \text{Mpc}^{-1}$ (Saha et al. 2001, Tammann et al. 2002). This implies possible ages of the Universe in the range 11-17 billion years, depending of the acceleration/deceleration history of the Universe itself.

However, even SNe Ia are not perfect standard candles. Their absolute magnitudes correlate with second parameters, like decline rate $\Delta m_{15}$, light curve shape, SN color, spectral features (possibly correlated with temperature), and Hubble type or color of the parent galaxy. Starting with Pskovskii (1977) and Phillips (1993), there exists a rich literature on the subject (for a review, see Parodi et al. 2000). Different empirical relations have been derived to homogenize the SN data, but there is no clear picture of the underlying physics (see e.g., Höflich & Khokhlov 1996). The second-parameter corrections are a serious problem because the nine calibrating SNe Ia have slower decline rates, are bluer, and lie in later-type galaxies than the distant SNe Ia. Consequently the resulting value of $H_0$ varies depending on which correction is adopted. The problem is accentuated by the fact that some authors exclude some of the calibrators on grounds of their age or alleged quality of their photometry, and/or include calibrators without direct
Cepheid distances. As a result current determinations of $H_0$ based on SNe Ia data vary between 55 (Schaefer 1998) and 71 (Freedman et al. 2001). According to a recent discussion by Panagia (2003a), the most probable value appears to be $H_0 = 63 \pm 6 \text{ km s}^{-1}\text{Mpc}^{-1}$.

3 Is the Universe accelerated?

Once the expansion rate is determined, the next step is to determine its variation in the course of the evolution of the Universe. It is interesting to note that, since one wants to measure the variation of the expansion rate, it is only necessary to verify that SNIa are indeed standard candles, that is that they have the same properties at all redshifts (or, equivalently, at all look-back times), with no need to determine their absolute luminosities. In other words, one could measure the deceleration parameters without measuring $H_0$, and vice versa. The acceleration of the Universe can be determined using SNIa as standard candles, if these are observed at suitably large distances in order to reveal a measurable deviation from a constant expansion.

Pioneering work by Danish astronomers Nørgaard-Nielsen and collaborators in the late 1980’s led to the discovery of one SNIa at redshift 0.31 as the result of a multi-year observational effort (Nørgaard-Nielsen et al. 1989). It was only when Perlmutter’s Supernova Cosmology Project (SCP) took off that SNIa searches at high redshifts became an efficient reality. The SCP is an international collaboration of researchers from the United States, Sweden, France, the United Kingdom, Chile, Japan, and Spain. Thanks to their use of large format detectors, a “clever” observational strategy, and sophisticated image analysis techniques (Goobar & Perlmutter 1995), in 1992 they discovered their first high redshift SNIa, SN 1992bi at $z = 0.46$ (Perlmutter et al. 1995), followed in 1994 by 6 more at $z > 0.35$ (Perlmutter et al. 1997). Currently they discover about a dozen SNIa during each observing run, typically twice a year.

Friendly competition promptly followed suit, when the High-Z Supernova Search Team, another international collaboration led by Brian Schmidt (Australian National University) started their systematic searches in 1995, essentially adopting Perlmutter’s strategy and, consistently, also discovering a dozen supernova candidates per run. By mid-1998 the SCP team had discovered and studied about 78 SNIa (Perlmutter et al. 1998, 1999), most of which in the redshift range 0.2–0.8, and the HZSS team had discovered about 32 SNIa (Riess et al. 1998).
In the last few years, both groups have augmented their SNIa samples and, for selected SNIa, have complemented their ground-based observations with much higher quality photometry obtained with the HST–WFPC2. The obvious improvement provided by the superior angular resolution of HST is that contamination by the host galaxy light is significantly reduced and becomes an easily treatable problem, thus providing higher photometric accuracy (see Figure 2).

When SCP and HZSS researchers initially set out to measure the expansion rate of the Universe, they expected to find that distant supernovae appeared brighter than their redshifts would suggest, indicating a slowing rate of expansion with time as the effect of gravitational attraction of all masses in the Universe. Instead they found the opposite: at a given redshift, distant supernovae were dimmer than expected (see Figure 3). Expansion was accelerating!

The SNIa evidence for acceleration was tightened up by the discovery and the study of SNIa at redshifts higher than 1. The most distant SNIa found so far is SN 1997ff. The supernova was discovered by Gilliland and Phillips (1998; see also Gilliland, Nugent & Phillips 1999) in a repeat HST-WFPC2 observation of the Hubble Deep Field North (HDF-N) and was serendipitously monitored with HST-NICMOS throughout Thompson and collaborators Guaranteed-Time-Observer campaign. Analysing the available HST data, Riess and collaborators (2001) determined the supernova...
Figure 3: SN Ia residual Hubble diagram comparing cosmological models and models for astrophysical dimming. Top: SNIa from ground-based discoveries in the top-quality sample are shown as diamonds; HST-discovered SNIa are shown as filled symbols. Bottom: Weighted averages in fixed redshift bins are given for illustrative purposes only. Data and models are shown relative to an empty universe model ($\Omega = 0$). High redshift supernovae exclude grey dust and/or monotonic evolutionary effects to explain the SNIa data and strongly favor the cosmological interpretation with $\Omega_M \sim 0.3$, $\Omega_\Lambda \sim 0.7$ (Riess et al. 2004).

The results obtained for additional high redshift SNIa (Knop et al. 2003, Tonry et al. 2003) provide strong support to the cosmological interpretation (see Figure 3) while excluding conclusively grey dust absorption and/or monotonically varying evolutionary effects, which could explain the dimming (relative to the expectations for an empty Universe) of SNIa up to $z \sim 0.5$, but definitely not the brightening as found for higher $z$ SNIa.

Most recently Riess et al. (2004b) reported the results of an HST search of high $z$ SNe. The search exploited the repeated observations (five epochs
at about 45 day intervals) of two fields of approximately 10′ × 15′, centered on the Hubble Deep Field North (HDF-N) and the Chandra Deep Field South, respectively, made by the Great Observatories Origins Deep Survey (GOODS) Hubble Space Telescope Treasury Program with the Advanced Camera for Surveys (Giavalisco et al. 2004). Photometric redshift measurements of the hosts combined with deep F606W, F775W, and F850LP imaging were used to discriminate hydrogen-rich SNe II from SNe I at $z > 1$ on the basis of a marked UV deficit in the energy distributions of SNIa (Panagia 2003b, Riess et al. 2004a). Subsequent spectroscopy of 11 GOODS SNIa obtained from the ground and with the grism on ACS confirmed the reliability of the photometric screening.

In this way 16 Type Ia supernovae were discovered and used to provide the first statistically “convincing” evidence for cosmic deceleration that preceded the current epoch of cosmic acceleration. These objects include 6 of the 7 highest redshift SNIa known, all at $z > 1.25$, and populate the Hubble diagram in unexplored territory. The luminosity distances to these objects and to 170 previously reported SNe Ia (Perlmutter et al. 1998, Riess et al. 1998, Perlmutter et al. 1999, Tonry et al. 2003, Knop et al. 2003) have been determined using empirical relations between light-curve shape and luminosity, based on local Universe measurements assumed to apply to high redshift objects as well. A purely kinematic interpretation of the SN Ia sample provides evidence for a transition from deceleration to acceleration that is constrained to be at $z=0.46 ± 0.13$. The data are consistent with the cosmic concordance model of $\Omega_M \sim 0.3, \Omega_\Lambda \sim 0.7$ and are inconsistent with a simple model of monotonic evolution with redshift, or extinction by grey dust as an alternative to dark energy.

For a flat Universe ($\Omega_{tot} = 1$; de Bernardis et al. 2000, 2002, Spergel et al. 2003) with a cosmological constant, Riess et al. (2004) measure $\Omega_M \sim 0.29 ± 0.04$ (equivalently, $\Omega_\Lambda = 0.71$). When combined with external constraints imposed by cosmic microwave background and large-scale structure measurements (e.g., Turner 2002), they find $w = -1.02 ± 0.16$ (and $w < -0.76$ at the 95% confidence level) for an assumed static equation of state of dark energy, $P = w\rho c^2$. These constraints are consistent with the static nature and value of $w$ expected for a cosmological constant (i.e., $w_0 = -1.0$, $dw/dz = 0$) and are inconsistent with a very rapid evolution of dark energy.

Thus, it appears that the Universe would never come to an end, and more fundamentally that a large part of the Universe is made of something we know nothing about – the mysterious whatever-it-is that goes by the
name of “dark energy” – that approximately 7 billion years ago overcame gravity and started pushing the Universe to an accelerated expansion.

The first attempt to explain the nature of dark energy was by invoking Albert Einstein’s notorious “cosmological constant,” an extra term he introduced in the equations of the theory of general relativity early in the 20th century under the mistaken impression, shared by astronomers and cosmologists of the time, that the Universe was static. The cosmological constant, which Einstein signified by the Greek letter \( \Lambda \), made it so. Einstein happily abandoned the cosmological constant when, in 1929, Edwin Hubble found that the Universe was not static but expanding. However, \( \Lambda \) came back.
strong - albeit 70 years later - when supernova studies led to the discovery that expansion was accelerating.

These results are rather unexpected and puzzling: for example, the fact that the cosmological constant value is comparable to the current mass density (which decreases with time) would place us at a “special” time in the evolution of the Universe. It is clear that the problem is far from solved, but can be solved: one needs to study more SNIa, over a wider range of redshifts to reduce the uncertainty region and to test for the presence of possibly “unseen” systematic effects, e.g., evolution of the SNIa properties with redshift and/or metallicity.

Currently, there are two leading interpretations for the dark energy as well as many more exotic possibilities. It could be an energy percolating from empty space as Einstein’s theorized “cosmological constant,” an interpretation which predicts that dark energy is unchanging and of a prescribed strength.

An alternative possibility is that dark energy is associated with a changing energy field dubbed “quintessence” (see e.g., Caldwell, Dave, & Steinhardt 1998). This field would be causing the current acceleration – a milder version of the inflationary episode from which the early Universe emerged. When astronomers first realized the Universe was accelerating, the conventional wisdom was that it would expand forever. However, until we better understand the nature of dark energy and its properties, other scenarios for the fate of the Universe are possible. If the repulsion from dark energy is or becomes stronger than Einstein’s prediction, the Universe may be torn apart by a future “Big Rip” (see e.g., Caldwell, Kamionkowski, & Weinberg 2003), during which the Universe expands so violently that first the galaxies, then the stars, then planets, and finally atoms come unglued in a catastrophic end of time. Currently this idea is very speculative, but being pursued by theorists. At the other extreme, a variable dark energy might fade away and then flip in force such that it pulls the Universe together rather than pushing it apart. This would lead to a “Big Crunch” (e.g., Endean 1997) where the Universe ultimately implodes.

4 Is there any room for a doubt?

As summarized by Riess et al. (2004), the potential for luminosity evolution of corrected SN Ia distances has been studied using a wide range of local host environments. No dependence of the distance measures on the host
morphology, mean stellar age, radial distance from the center, dust content,
or mean metallicity has been seen (Riess et al. 1998; Perlmutter et al.
1999; Hamuy et al. 2000). No differences in the inferred cosmology were seen by
Sullivan et al. (2003) for SNIa in early-type hosts or late-type hosts at high
redshifts. These studies limit morphology dependence of SN Ia distances
to the 5% level. Detailed studies of distance-independent observables of
SNIa, such as their spectral energy distribution and temporal progression,
have also been employed as probes of evolution (see Riess 2000, Leibundgut
2001, and Perlmutter & Schmidt 2004 for reviews). The current consensus is
that there is no evidence for evolution with limits at or below the statistical
constraints on the average high-redshift apparent brightness of SNIa. The
observed nominal dispersion of high-redshift SNIa substantially limits the
patchiness of uncorrected extinction, and near-IR observations of a highredshift
SN Ia demonstrate that a large opacity from grayish dust is unlikely
(Riess et al. 2001).

The case, therefore, would appear to be water-tight as long as all SNIa
events have one and the same origin. However, this may not be quite true.

4.1 SNIa properties in the local Universe

In a recent study, Mannucci et al. (2005) have determined the rate of super-
novae (SNe) of different types along the Hubble sequence as a function of
both the near-infrared luminosity and the stellar mass of the parent galax-
ies. They find that the rates of all SN types, including Ia, Ib/c and II, show
a sharp dependence on both the morphology and the (B–K) colors of the
parent galaxies and, therefore, on the star formation activity. In particular
the SN Ia rate in late type galaxies turns out to be a factor \( \sim 20 \) higher
than in E/S0 galaxies. Similarly, the SN Ia rate in galaxies bluer than B–
K=2.6 is about a factor of 30 greater than in galaxies with B–K>4.1. These
findings are clear evidence that a significant fraction of Ia events in late
Spirals/Irregulars originates from a relatively young stellar component.

An independent indication of different channels to produce SNIa explo-
sions is provided by the study of the frequency of SNIa events occurred in
elliptical galaxies. An analysis of SNIa events in large sample of early type
galaxies (Della Valle & Panagia 2003, Della Valle et al. 2005) unambiguously
shows that the rate of type Ia Supernovae (SNe) in radio-loud galaxies is
about 4 times higher than the rate measured in radio-quiet galaxies. The ac-
tual value of the enhancement is likely to be in the range \( \sim 2−7 \) (P\( \sim 10^{-4} \)).

Discussing the possible causes of the SNIa rate enhancement in radio-
loud ellipticals, Della Valle et al. (2005) conclude that this phenomenon has the same common origin that determines these galaxies to be strong radio sources, but that there is no causality link between the two phenomena. In particular, they argue that repeated episodes of interaction and/or mergers of early type galaxies with dwarf companions, on timescale of $\sim 1\text{Gyr}$, are responsible for inducing both strong radio activity in early type galaxies and to supply an adequate number of “fresh” SNIa progenitors to the old (Population II) stellar population of ellipticals.

### 4.2 Will two types of SNIa spoil the party?

Considering the systematic diversity of SNIa in the local Universe, the use of one and the same kind of SN Ia as cosmological standard candles may be questioned (for a more detailed discussion, see Mannucci, Della Valle & Panagia 2005).

From the study by Mannucci et al. (2005), it appears that in the local Universe there are two distinct populations of progenitors of SNIa, each characterized by very different delay times, i.e. characteristic times between star formation and stellar explosion. About half of the SNIa originate from a relatively young stellar population, whose progenitors explode after a short delay time (say, $<100\text{ Myrs}$) since their formation (“prompt” SNIa), and may be the result of the merging of two degenerate stars in a binary system. The other half (“tardy” SNIa) comes from older stellar populations and their progenitors explode with delay times of 2–4 Gyrs (e.g., Strolger et al. 2004, Gal-Yam & Maoz 2004), and possibly originate from a binary system composed of a white dwarf and an ordinary star. It is easy to realize that these two species of SN Ia will not be equally frequent at all redshifts: the prompt exploders dominate at high redshifts where the star formation is particularly active, whereas the tardy exploders become the dominant species in the less distant Universe where the overall star formation rate is rapidly declining.

This would not be a problem if it was not that SNIa originating in different environments appear to have peak luminosities appreciably different from each other. In particular, in the local Universe, SNIa occurring in late type galaxies are found to be systematically brighter by several tenths of a magnitude than SNIa occurring in early type galaxies (Filippenko 1989, Della Valle & Panagia 1992, Hamuy et al. 1996, Howell 2001). Extending this trend to all redshifts, one would predict the alarming effect that SNIa at redshifts less than 0.5-1 would be intrinsically dimmer than SNIa occurring...
at higher redshifts, \( z > 1 \), which is just the behaviour that is regarded as proof for acceleration. As a result, all quantitative conclusions about the acceleration of the Universe would have to be drastically revised, if not even reversed (i.e., there might not be any acceleration...).

Curiously enough, Sullivan et al. (2003), from a thorough analysis of all samples available at the time, found marginal evidence that at high redshifts SNIa occurring in early type galaxies are \( 0.14 \pm 0.09 \) magnitudes brighter than the ones occurring in late type galaxies. They attribute this difference to the effect of dust extinction that is non negligible in late type galaxies whereas early type galaxies are essentially dust-free.

The fact that a fair extrapolation of well established properties observed for SNIa in the local Universe be at variance with what appears to be the case at high redshifts is puzzling. It could indicate that there are unsuspected evolutionary effects that end up canceling each other out, or that the statistics and/or the accuracy of the measurements of SNIa events is not adequate to provide an unambiguous answer. In both cases, it appears that the problem of whether there is an acceleration in the Universe, and if so what its strength is, is not definitely solved and that much work is still needed before reaching the final conclusion.

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