A REVIEW OF THE HIGH-REDSHIFT SUPERNOVA SEARCHES

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Observations show that Type Ia Supernovae (SNe Ia) form a homogeneous class of objects. They share similar spectroscopic evolution, light-curve shapes, and peak absolute magnitudes. The slight departures from homogeneity that are observed can be used to produce a “calibrated candle” with corrected magnitudes with even smaller dispersion. The existence of this intrinsically bright distance indicator has inspired two coordinated high-redshift supernova searches: the Supernova Cosmology Project and the High-z Supernova Search Team. To date \( \sim 100 \) SNe Ia have been discovered by the two groups. The preliminary analysis of the first of these objects demonstrate how well SNe Ia can be used to measure the mass density of the universe \( \Omega_M \) and the normalized cosmological constant \( \Omega_\Lambda \equiv \Lambda/3H_0^2 \).

1 Introduction

For the past several years, two independent groups have been discovering and following high-redshift supernovae \((z > 0.3)\) using telescopes from all over the world and beyond. The lofty and imposing goal of these searches? To determine the ultimate fate of the universe! But before I tell you what the answer is (so far), I should explain what makes supernovae so special and give you an idea of what’s been observed to date. Then comes the answer, along with a discussion of some of the systematic errors involved and how we can address them. I conclude by presenting the scientific course we plan to take in the near future.

2 Type Ia Supernovae as Distance Indicators

One of the big reasons that supernovae are exciting for cosmologists is because of the remarkable homogeneity of the type Ia’s (SNe Ia)\(^*\). This homogeneity is seen in their evolving spectra

\(^*\)The supernova classification system is empirical and is based on the spectrum, SNe Ia exhibit no hydrogen (hence the “I”) and have strong silicon P-Cygni features (hence the “a”) during their photospheric phase.
(Filippenko\cite{Filippenko1}), their light-curve shapes (Leibundgut\cite{Leibundgut2}), and their peak absolute magnitudes which have a dispersion of $\sigma \approx 0.3 - 0.5$ mag depending on the sample (Branch and Tammann\cite{Branch3}). SNe Ia are also whoppingly bright, at peak they can emit as much light as their host galaxy. This combination of brightness and homogeneity means that they can be used to measure distances out to very high redshifts.

The standard model for the SNe Ia progenitor system has a white dwarf in a binary system accreting matter from its companion until it reaches the Chandrasekhar mass ($\sim 1.4M_\odot$) triggering a thermonuclear runaway which we observe as a supernova. This idea neatly explains the homogeneity and the lack of hydrogen in the spectra. Detailed theoretical work has provided strong support for this model (Nomoto et al.\cite{Nomoto4}) although there are a few outstanding questions that have to be resolved, for example the nature of the binary companion and the hydrodynamics of flame propagation.

Strong evidence for intrinsic inhomogeneity first came with the light curves of the Calán-Tololo supernova search. It was shown that the light-curve shape was correlated with the supernova peak brightness in such a way that the slow decliners tend to be brighter than the rapid decliners (Hamuy et al.\cite{Hamuy5}; Riess, Press, and Kirshner\cite{Riess6}). The slow decliners were also bluer in the optical passbands (Riess, Press, and Kirshner\cite{Riess7}) and had a much stronger UV flux (Branch, Nugent, and Fisher\cite{Branch8}). The line ratios of particular spectral features at maximum light also vary with light-curve shape, an effect that has been modeled as being due to differences in the supernova’s photospheric temperature (Nugent et al.\cite{Nugent9}).

We can take advantage of this inhomogeneity by using relations between the absolute magnitude and these other independent observables to produce a “calibrated candle” with an even tighter absolute magnitude dispersion than before. Such corrections using light-curve shapes yield corrected magnitude dispersions of $\sigma \approx 0.18$ mag.

Note that $M = M - 5\log H_0 = m - 5\log(\text{cz})$ is the “absolute magnitude” accurately measured for supernovae in the Hubble flow. It is not sensitive to the uncertainty in the Hubble constant and so is used in lieu of the true absolute magnitude.

### 3 The Searches

There are currently two independent teams that are running coordinated search and follow-up observations of high-redshift supernovae. They are the Supernova Cosmology Project (SCP) (Perlmutter et al.\cite{Perlmutter10}) which was launched in 1989, and the High-Z Supernova Search Team (HIZ) (Garnavich et al.\cite{Garnavich11}) which found their first supernova in 1995. Both teams use similar techniques (described in detail in Perlmutter et al.\cite{Perlmutter12}) and resources as follows.

A special strategy is needed to find these rare and random events. Several days after new moon, a series of wide-field images are taken on a 4-m class telescope, with each field containing over a thousand galaxies that can potentially host a supernova. Several weeks later the same fields are re-observed and scanned for new point sources. After applying cuts to reject asteroids, AGN, quasars, cosmic rays, and other sources of background, we are left with supernova candidates. Having run the search right before new moon we have optimal observing conditions for pre-scheduled spectroscopy to identify the candidates, and photometry to build their multi-band light curves. The three week gap in the search is well matched for the $\sim 20$ day (rest frame) rise time for SNe Ia, meaning that most all the supernovae will be discovered before or at maximum light. With the allocated search time (typically a pair of two nights) both groups have been yielding $\sim 12$ supernovae per run.

Most of the current searching is performed on the 30’x30’ field of the BTC at the CTIO Blanco Telescope. With its 10-m diameter collecting area, the Keck Telescope is the spectroscopic workhorse for both groups, allowing us to efficiently observe and confirm a large number of faint candidates. Photometric follow-up is performed at a host of 2 to 4-meter telescopes all
around the world.

In total, there have been \( \sim 100 \) SNe Ia with spectral confirmation discovered at \( z > 0.3 \) by the two groups. Histograms describing their redshift distributions are given in Figure [1]. The mean redshifts of the discovered supernovae have been steadily increasing with each successive search run, as we have specifically tailored the filters and exposure times to search at progressively larger distances.

Even though we have been chugging along doing practically the same thing for several years, there are a couple of new developments that I find exciting. We now have found \( 4 \) supernova with \( z > 0.8 \) and we expect that number to grow quickly. By pushing our detectors to the limit, we could search even deeper than we are now. (The furthest supernova to date with a confirmed SN spectrum is SN1998I at \( z = 0.89 \), discovered by the HIZ group.) Both groups have scheduled HST time for photometric follow-up, giving us precise photometry and host morphology identification. Furthermore, at higher redshifts a supernova’s rest-frame optical light reaches us in the infra-red. The HST NICMOS camera (while it lasts) gives us a superior morphology identification. Furthermore, at higher redshifts a supernova’s rest-frame optical light reaches us in the infra-red. The HST NICMOS camera (while it lasts) gives us a superior view in this wavelength regime than would be possible from the ground. The first results using the HST data have already been published (Perlmutter et al. [4]; Garnavich et al. [4]).

4 Measurement of \( \Omega_M \) and \( \Omega_\Lambda \)

By using SNe Ia as distance indicators, we can measure the cosmological parameters. The standard Friedmann-Lemaître cosmology gives a magnitude-redshift relation as a function of \( \Omega_M \) and the normalized cosmological constant \( \Omega_\Lambda \equiv \Lambda/3H_0^2 \):

\[
m_R(z) = M_B + 5 \log(D_L(z; \Omega_M, \Omega_\Lambda)) + K_{BR},
\]

where \( K_{BR} \) is the K correction relating \( B \) magnitudes of nearby SNe with \( R \) magnitudes of distant objects (Kim, Goobar, and Perlmutter [4]) and the “absolute magnitude”, \( M_B \), is determined using local supernovae in the Hubble flow. (Recall that it is \( M_B \) that depends on the light curve shape.) Here we use \( D_L \), the “Hubble-constant-free” part of the luminosity distance, \( d_L \):

\[
D_L(z; \Omega_M, \Omega_\Lambda) \equiv d_LH_0 = \frac{c(1+z)}{\sqrt{|\kappa|}} S\left(\sqrt{|\kappa|}\int_0^z \left[(1+z')^2(1+\Omega_M z') - z'(2+z')\Omega_\Lambda\right]^{-\frac{1}{2}} dz'\right),
\]

where for \( \Omega_M + \Omega_\Lambda > 1 \), \( S(x) \) is defined as \( \sin(x) \) and \( \kappa = 1 - \Omega_M - \Omega_\Lambda \); for \( \Omega_M + \Omega_\Lambda < 1 \), \( S(x) = \sinh(x) \) and \( \kappa \) as above; and for \( \Omega_M + \Omega_\Lambda = 1 \), \( S(x) = x \) and \( \kappa = 1 \), where \( c \) is the speed of light in units of km s\(^{-1}\).

What these equations show is that the difference between the absolute and observed magnitudes of a supernova at a given redshift corresponds with a strip (a line if we don’t include uncertainties) in the \( \Omega_M - \Omega_\Lambda \) plane. Furthermore, the shape and orientation of the band are different at different redshifts, meaning that supernova measurements from a wide range of redshifts have confidence regions whose intersection gives a closed area in the \( \Omega_M - \Omega_\Lambda \) plane (Goobar and Perlmutter [4]). This allows us to make a simultaneous measurement of \( \Omega_M \) and \( \Omega_\Lambda \) with the added bonus the answer does not depend on the Hubble constant.

Both groups have published results from the first handful of supernovae found (Perlmutter et al. [4]; Perlmutter et al. [4]; Perlmutter et al. [4]; Garnavich et al. [4]). I will present here the preliminary results from the analysis of the first \( \sim 40 \) supernovae from SCP. Results from the HIZ collaboration are presented in Leibundgut’s paper in these proceedings and a new paper based on their first \( \sim 15 \) events is in the works.

Figure [2] shows the preliminary confidence regions in the \( \Omega_M - \Omega_\Lambda \) plane for the first \( \sim 40 \) SCP supernovae. The length of the region shows that at the moment we cannot simultaneously
Figure 1: The redshift distributions of the SNe Ia found by the two searches. Note that four of the first seven SCP supernovae shown do not have spectroscopic confirmation.

Figure 2: Preliminary confidence regions from the first ∼ 40 SCP supernovae. The confidence regions are strictly statistical, the lower contours show the results if there is a 0.2 magnitude systematic difference between local and distant supernovae.
constrain $\Omega_M$ and $\Omega_{\Lambda}$ down to an interesting level because we currently lack a large number of $z > 0.8$ supernovae. The skininess of the region is due to the reduced statistical error from the large number of supernovae observed at $z \sim 0.5$. It allows us to make statistically significant measurements of the cosmological parameters if we assume a flat ($\Omega_M + \Omega_{\Lambda} = 1$) universe, $\Omega_M = 0.025 \pm 0.06 \pm 0.3$, or a $\Lambda = 0$ universe, $\Omega_M = -0.4 \pm 0.1 \pm 0.5$, where the first error is statistical and the second is an estimate of systematic error. Of profound interest is the fact that our supernovae strongly disfavor the flat $\Lambda = 0$ universe predicted by the simplest theories of inflation. Fortunately the HIZ team is getting similar results.

5 Systematics

It’s clear that our results are now limited by systematic errors and that these errors need to be seriously addressed. The confidence regions shown in Figure 2 are calculated using only our statistical uncertainty. To illustrate the effect of systematic errors, we plot a second set of contours in Figure 2, which show how our confidence region would shift if high-redshift supernovae were systematically 0.2 mag fainter than the nearby calibrators, (while maintaining the same light-curve shapes). Systematic errors generally have the effect of shifting our contours in the $\Omega_M - \Omega_{\Lambda}$ plane, smearing the confidence of our measurement. Detailed descriptions of how we handle some of these systematics are given in Perlmutter et al. 16

Malmquist bias is a fancy way of saying that in a magnitude limited sample, we are more likely to observe intrinsically brighter objects. For a given redshift, this produces a shift in the mean observed magnitude as compared to the intrinsic mean. Such an effect in our distant supernova would cause us to overestimate $\Omega_M$ so corrections for this effect would move us even further from a $\Lambda = 0$ flat universe. To measure the influence of Malmquist bias, we have determined the detection efficiencies and thresholds for our search and performed a fit using only the subsample of supernovae found far from the detection limit; no statistically significant change in $\Omega_M - \Omega_{\Lambda}$ is seen. More disturbing is the fact that the effect of Malmquist bias on the local calibrators is not easily calculable. Many of the nearby supernovae were found either randomly or on photographic plate searches. A correction for Malmquist bias in the nearby sample would move us closer to a $\Lambda = 0$ flat universe. What is now needed is a determination of the intrinsic population of SNe Ia from a large sample of local supernovae found in CCD searches with known detection efficiencies. The similar distributions currently seen in high-z and local light-curve shapes do indicate there is no large relative difference in the effect of Malmquist bias in the two samples.

There is no guarantee that local and distant supernovae are exactly the same. One may expect systematic differences in the progenitor system metallicity or in the white dwarf $C/O$ ratio. Our most powerful test for evolution is with the comparison of distant and nearby supernova spectra, because in spectra we should see the effects of different initial progenitor compositions (Höflich, Wheeler, and Thielemann 13). Fortunately no such spectral redshift evolution has been noted in the spectra observed to date, e.g. SN1997ap at $z = 0.83$ (Perlmutter et al. 13). Important information could also come from supernovae at $0.1 < z < 0.3$ because it is feasible to obtain spectral time series which could show the first effects of redshift evolution.

In order to see the effect of extinction, we have compared the k-corrected color distributions of the local and distant supernovae. The negligible difference between the two indicates that the samples have similar $E(B - V)$ distributions. We also directly fit $E(B - V)$ for each supernova using the multi-band data and again find similar distributions for the two sets. Work is currently being performed to try to reduce the errors involved in individual supernova corrections. The fairly large uncertainty in $B - V$ for supernova at maximum as a function of light-curve shape translates into a large correlated uncertainty in magnitude absorption. In addition the extinction properties ($R_B$) at high-redshift are not well known.
There are population effects that can be seen in local supernovae. For example, supernovae in ellipticals on whole have skinnier light curves and are fainter than their spiral counterparts. The magnitude–light-curve shape relation in principle corrects such effects. However, considering all the possible population dependencies, we would like to select local and distant supernovae subsets that share as many population characteristics as possible. The steady stream of new nearby supernovae coming from a wide range of environments will allow us to do this.

We currently believe that we understand the effects of most of these systematics, at least to first order. We await new data from high-quality nearby supernovae searches to confirm our findings and to give us even stronger constraints on our errors. Specifically, the new data will supply us with the intrinsic supernova luminosity function and a large homogeneous set of light curves that start before maximum. The data will also provide us with large sample from which we can select subsamples with which to explore systematic errors.

6 Conclusion

We can confidently say that our data disfavors an $\Omega = 1, \Lambda = 0$ universe, considering the huge amount of systematic error required to make the two consistent. For the future, we need to pursue two opposite directions in order to get a more precise value of the cosmological parameters. By finding more supernovae at $z > 0.8$, we will attempt to reduce the length of the contour in Figure 2 to give a better simultaneous measurement of $\Omega_M$ and $\Omega_{\Lambda}$. By finding supernovae at $z < 0.2$ we will learn more about their intrinsic properties and give a larger sample with which we can study and hopefully reduce systematic effects. SCP is now dedicating a large part of its efforts in nearby supernova searching, and in collaboration a group of French scientists is planning to use the CFHT specifically for $z > 0.8$ searches. (HIZ’s most distant candidate was in fact found using the CFHT). Members of the HIZ team are already heavily involved in nearby searches and as a whole are pursuing higher redshifts. With all this focused activity, reduction of the systematic and statistical errors should not be far off in the future.

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