MEASUREMENTS OF FAINT SUPERNOVAE

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ABSTRACT.
We summarize the current status of cosmological measurements using SNe Ia. Searches to an average depth of $z \sim 0.5$ have found approximately 100 SNe Ia to date, and measurements of their light curves and peak magnitudes find these objects to be about 0.25 fainter than predictions for an empty universe. These measures imply low values for $\Omega_M$ (0.2-0.3) and a positive cosmological constant, with high statistical significance. Searches out to $z \sim 1-1.2$ for SNe Ia (peak magnitudes $m_I \sim 24.5$) will greatly aid in confirming this result, or demonstrate the existence of systematic errors. Multi-epoch spectra of SNe Ia at $z=0.5$ are needed to constrain possible evolutionary effects. I band searches should be able to find SNe Ia out to $z \sim 2$. We discuss some simulations of deep searches and present histograms of type Ia and type II SNe discovery statistics at several redshifts.

1. Cosmology with SNe Ia
Measuring the global curvature and cosmic deceleration (often parameterized as $q_0$) of the Universe has been a fundamental question in astronomy ever since Robertson(1936) and Walker(1936) first formulated the metric for a homogeneous and isotropic universe. Although many methods for measuring the global properties of space exist, none has yet delivered anything close to a definitive measurement. By tracing how a standard candle dims as a function of redshift, usually shown as a Hubble diagram, the effects of global curvature and deceleration can be seen and quantified.

Two groups are currently using intensive observations of SNe Ia to map the universe in search of these effects. Our group, the High-Z SN search, is led by Brian Schmidt at MSSSO. The other effort the Supernovae Cosmology Project, is led by S. Perlmutter at the Lawrence Berkeley Laboratory.

Local ($z < 0.15$) calibration is provided by $\sim 50$ SNe, the majority from the Calan-Tololo search (Hamuy et al. 1996) and the work of the Harvard group (Riess et al. 1999). Following work by Phillips (1993), it is clear that the maximum luminosity of a SN Ia event is highly correlated with its decline rate from maximum light, which can then be used to improve the accuracy of SNe Ia distances (Hamuy et al. 1996b; Riess et al. 1995).

For the high-z sample, both groups primarily search at the prime focus of the CTIO Blanco 4m, using the BTC, a mosaic CCD camera provided by J. A. Tyson and G. Bernstein. With 5-minute integrations and a 29′ field we reach a limit of $m_R \sim 24$, depending on image quality, and can survey approximately 6 square degrees per night (Schmidt et al. 1998). With deeper I band searches at CTIO and at the CFHT with
the University of Hawaii 8k mosaic imager, we have found SNe out to redshifts of $z \sim 1$. Spectra for redshifts and classification are taken at ESO, the MMT and Keck, and addition photometry for light curve fitting has used 2-4m telescopes at WIYN, ESO, MDM, CTIO and ARC.

Recent work by both teams (Riess et al. 1998, Permuter et al. 1999) has shown that Type Ia supernovae at $z \sim 0.5$ are about $0.\text{m}^{25}$ fainter than the simple predictions for an empty universe. Figure 1 shows the latest version of the Hubble diagram from the High-Z team. Our value of $\Omega_M$ is low, $\sim 0.24-0.28$, depending analysis techniques and exact sample composition. More surprisingly, the analysis yield a conclusion that $\Omega_\Lambda > 0$ at a more than $3\sigma$ confidence level. These measurements, particularly when combined with the current measures of the first Doppler peak of the cosmic background radiation (Hancock et al. 1998), provide strong evidence for $\Omega_T \sim 1$ (Garnavich et al. 1998; Efstathiou et al 1999). Our analysis yields $\Omega_M + \Omega_\Lambda = 0.94 \pm 0.26$.

Figure 2 shows that the maximum effect of the presence of a positive cosmological constant (with respect to an empty universe) occurs around $z \sim 0.85$. If the faintness of the SNe Ia at $z=0.5$ is due to a positive $\Omega_\Lambda$, then at higher redshift supernovae should not get fainter. By $z=1.2$, they should even begin to brighten with respect to an empty universe. On the other hand, if the fading is due to some systematic error, such as grey dust or evolution, one would expect the faintness of to increase with redshift. In Figure 2 we show what happens if there is a systematic error that is consistent with our $z=0.5$ data, but grows linearly with $z$. Thus one of the major efforts we are currently undertaking is to search for SNe between $z=0.8$ and $z=1.2$. 

![Hubble Diagram](image-url)
Fig. 2. The SNIa data are plotted relative to an empty universe. The thin curves are the best fitting $\Lambda$ model, and an $\Omega_M = 1$ model. The heavy curve shows an example of a systematic bias which increases linearly with $z$ and is consistent with our $z = 0.5$ data. The dark points show the redshifts and experimental uncertainty of the proposed observations at $z = 0.85$ and $z = 1.2$.

1.1. Spectroscopy of Faint SNe Ia

One of the most worrisome systematic effects is source evolution. Evolution has been the death of other methods used to trace luminosity distances with redshift. There are strong hints from the low-redshift samples (Hamuy et al. 1996a) that the most luminous supernovae are found in later type galaxies, and that the SN Ia rate per unit luminosity is twice as high in late-type galaxies as in early-type. This suggests that the luminosity of the supernovae in a galaxy depends on the age of the stellar population. Recent attempts (Hoflich, Wheeler & Thielemann 1998) to model effects of metallicity, C/O ratio, or changes in progenitor age are still preliminary. The metallicity changes are greatest in rest-frame UV spectra or light curves (e.g., rise times), and might be discernible in high S/N spectra. Younger white dwarf progenitors are expected to have a lower C/O ratio, and this could redden the SN at maximum and steepen the luminosity decline.

If evolution of SNe Ia is causing the objects to be fainter at $z \sim 0.5$ (contrary to initial model predictions), we would expect this effect to continue at higher redshifts and thus deeper searches will be helpful as mentioned above. But we are also concentrating on obtaining high quality data on our $z=0.5$ sample. We are obtaining rest frame B and V light curves with HST for 4 SNe in tandem with multi-epoch Keck spectra in order to compare rigorously the distant objects to the nearby sample.

In Figure 3 we show a spectral comparison for a supernova discovered in Jan 1999 (Filippenko et al. 1999). To obtain good S/N (>10:1) at moderate resolution (R~1000) at magnitudes fainter than $m_R \sim 23$ requires exposures of several hours with the Keck 10m telescope. To obtain similar quality spectra at $z \sim 1$ requires working at magnitude $m_I \sim 24-25$, which will be very challenging for the current generation of ground
based telescopes. Up to this point, comparisons of spectra at $z=0.5$ show no significant differences from their low redshift brethren (see also Riess et al. 1998).

2. Supernovae at $z>1$

Due to the rapid flux increase above 2600Å, SNe Ia can be found in I band images from CCD cameras out to redshifts of $z\sim2$. While most such efforts continue to use ground-based techniques, because of the wide field capabilities of those telescopes, several SNe have been discovered using HST. Gilliland, Nugent and Phillips (1999; hereafter GNP) detected two likely supernovae events in a revisit to the Hubble Deep Field (HDF) with WF/PC2. With a baseline of 2 years and a shorter I band (only) exposure (63000 sec), two objects were detected at $m_I\sim26$ and 27. These were associated with galaxies at redshifts 0.95 (spectroscopic) and 1.32 (photometric). This second event is the highest-$z$ SN Ia discovered to date (although of course no confirming spectrum of the SN was obtained), and appears to be associated with an elliptical galaxy, based on colors and profile fitting.

GNP performed detailed calculations to quantify the number of expected SNe in the HDF at a given epoch. The number of SNe expected depends on: 1) the adopted cosmology; 2) the SN rate per unit redshift; and 3) modeling of the length of time a given SN remains visible. Calculation of the rates involves models for the progenitors of types I and II supernovae, assumed initial mass functions and parameterized delay times after White Dwarf formation. These calculations follow studies of the star formation history of the universe (e.g., Madau, Valle & Panagia 1998). Knowledge of both the
light curves and spectral evolution of SNe is necessary to model the length of time SNe at different redshift remain visible, and we are limited by our imperfect knowledge of the UV behavior of SNe. The heterogeneous nature of type II SNe also contributes to the complexity of these calculations.

In Figure 4 (from GNP) is shown the light curves of extinction-free SNe Ia between $0.25 < z < 1.75$. These involve adoption of a zero-point for SN Ia (e.g., Suntzeff et al. 1999), and a characterization of the light curve shape, which relates the peak magnitude, color, and decay time of the SN event. GNP chose to parameterize these effects using the stretch-factor, $s$, (following Perlmutter et al. 1999). A stretch-factor of $s=1$ is used for the calculations in Figure 4. Interpolation of existing spectra for SNe Ia (particularly in the UV), and a detailed prescription for the K-correction is necessary to perform these calculations. A similar analysis is used by GNP to produce light curves for type II SNe.

GNP then proceed to calculate rates for the HDF field, based on observed rates at $z=0.5$ for SNe Ia (Pain et al. 1996) and Cappellaro et al. (1997) for type IIs. Figure 5 from GNP shows histograms based on Monte Carlo simulations of the relative number of SNe per magnitude interval in the HDF for redshifts of $z=0.95$ and 1.3 respectively. For the SNe Ia, they assume a constant volume rate as a function of redshift, a rather conservative approach. For the type II events they use an enhancement in SFR between $z=0$ and $z=2$ of a factor of 4, rather than more extreme values of up to 10 which have sometimes been proposed.

For the lower redshift case (Figure 5a), the histograms are consistent with existing ground-based searches. Down to 24th magnitude, type II SNe appear at 10-20% of the frequency of type Ia. At any given redshift, the SNe Ia events peak about 1.5-2 magnitudes brighter than the type II events. At fainter magnitudes at a given redshift, the type II objects will dominate mainly due to their higher intrinsic rate. The results
at $z=1.3$ are qualitatively similar in nature, although shifted about 1 mag fainter, and the type II peak at $m_I=27$ is compressed due to their cutoff limit at 27.7.

Due to the uncertainties of many of the input parameters and the variation of cosmic SFR with redshift, the absolute rates predicted in any simulations such as these are uncertain by factors of 2-3. Dahlen and Fransson (1999) predict a total about 300 SNe per square degree down to $I_{AB}=27$, about 1/3 of these being type Ia. This limit is likely reachable for imaging surveys with 8-10m ground-based telescope. A typical redshift will be $z\sim 1$, which an extended redshift distribution to $z\sim 2$. They also predict that NGST will be able to find $\sim 50$ SNe per pointing (at a limit of $K'=31.4$), about 20% of these type Ia. About 1/3 of the type II SNe should have $z>2$.

Fig. 5. Histogram of (simulated) discovery magnitudes for three types of SNe at $z=0.95$ (a) and $z=1.3$ (b). From Gilliland et al.

Sorting out the redshifts and types of these SNe will be a challenging task. Direct spectroscopy will be very difficult for existing 8-10m telescopes below 25th magnitude, i.e., a couple of magnitudes brighter than the imaging limit. In principle the SNe type can be determined from careful photometry of the light curves. In order to perform such a characterization, however, the decline must be followed with multiple observations (7-10) over more than a month, while the SN fades 1-2 magnitudes. Thus light curves are also limited to objects 1-2 magnitudes above the discovery limit. Photometric redshifts of the host galaxies may be possible in some cases, although a significant fraction of the SNe occur in dwarf or low surface brightness objects; in existing 4m SNe searches the SNe is almost always significantly brighter than its host. Dahlen and Fransson (1999) discuss the possibility of determining photometric redshifts from the SN light directly, but the time evolution and variety of spectral energy distributions for the range of SNe types makes this a very difficult proposition. Thus it is hard to escape the conclusion that we soon will need spectroscopic capability at $m_I\sim 26-27$, and this need will become even more important with the arrival of capabilities like NGST.
3. Other Things that Erupt in the Night

During our high-z searches we have discovered a few objects which fade very rapidly. We have at least 4 of these objects, approximately a factor of 10 down from our SNe Ia detection rate. Peak magnitudes are $m_R \sim 23-24$, with a time scale of between a few hours and a few days. These objects are hard to detail, since so little follow up observations are available. One possibility is that these objects are “optical” GRBs, i.e., we are detecting unbeamed optical radiation from a GRB pointed in some other direction. Another possibility is that these are SNe II in the brief high UV/optical luminosity phase, immediately after shock breakout (Blinnikov et al. 1998).

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References

Blinnikov, S. I., et al. 1998 Astrophys. J. 496, 454.
Cappellaro, E. et al. 1997 Astron. Astrophys. 322, 431.
Dahlen, T & Fransson, C. 1999, in press. [astro-ph/9905201].
Efstathiou, G. et al. 1999 Mon. Not. R. Astr. Soc. 303, L47.
Filippenko, A. V. et al. 1999, in preparation.
Garnavich, P. et al. 1998, Astrophys. J. 509, 74.
Gilliland, R., Nugent, P., & Phillips, M. M., in press [astro-ph/9903229].
Hamuy, M. et al. 1996a Astron. J. 112, 2391.
Hamuy, M. et al. 1996b Astron. J. 112, 2398.
Hancock, S. et al. 1998 Mon. Not. R. Astr. Soc. 294, L1.
Hofflich, P., Wheeler, J.C., & Thielemann, F.K., 1998 Astrophys. J. 495, 617.
Madau, P., Valle, M. D. & Panagia, N. 1998 Mon. Not. R. Astr. Soc. 297, L17.
Pain, R., et al. 1996 Astrophys. J. 473, 356.
Perlmutter, S. et al. 1999, in press [astro-ph/9812133].
Phillips, M. M., 1993, Astrophys. J. 413, L105.
Riess, A. G., Press, W. H., & Kirshner 1995, Astrophys. J. 438, L17.
Riess, A. G., et al. 1998, Astron. J. 116, 1009.
Riess, A. G. et al. 1999, Astron. J. 117, 707.
Robertson, H.P. 1936, Astrophys. J. 83, 187.
Schmidt, B. et al. 1998, Astrophys. J. 507, 46.
Suntzeff, N. B. et al. 1999, Astron. J. 117, 1175.
Walker, A. G. 1936 Proc. Lond. Math. Soc., 42, 90.