THE TYPE IA SUPERNOVA RATE AT $z \sim 0.4$

The Supernova Cosmology Project: IV

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Abstract. We present the first measurement of the rate of Type Ia supernovae at high redshift. The result is derived using a large subset of data from the Supernova Cosmology Project as described in more detail at this meeting by Perlmutter et al. (1996). We present our methods for estimating the numbers of galaxies and the number of solar luminosities to which the survey is sensitive, the supernova detection efficiency and hence the control time. We derive a rest-frame Type Ia supernova rate at $z \sim 0.4$ of $0.82\,^{+0.54}_{-0.37}\,^{+0.42}_{-0.32}\,h^2$ SNu where the first uncertainty is statistical and the second includes systematic effects.

1. Introduction

Beginning with the discovery of SN 1992bi (Perlmutter et al 1995), we have developed search techniques and rapid analysis methods that allow systematic discovery and follow up of "batches" of high-redshift supernovae.

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The observing strategy developed compares large numbers of galaxies in each of ∼50 fields observed twice with a separation of ∼3 weeks. This search schedule makes it possible to precisely calculate the "control time," the effective time during which the survey is sensitive to a Type Ia event.

For this analysis, we have studied a set of 52 similar search fields observed in December 1993 and January 1994. The data were obtained using the "thick" 1242×1152 EEV5 camera at the 2.5m Isaac Newton Telescope, La Palma. The projected pixel size is $0.56''$, giving an image area of approximately $11' \times 11'$. Exposure times were 600s in the R_{Mould} filter, and the images typically reach a 3σ limit of $R = 23$mag. Seeing was typically around $1.4''$. Many of the fields were selected due to the presence of a high-redshift cluster ($z \sim 0.4$). Suitable clusters and their redshifts were taken from Gunn, Hoessel & Oke (1986) and from the ROSAT catalog. The total useful area covered in this study is 1.73 sq deg.

The analysis procedure and method for finding SNe can be summarized as follows. For most fields, two first-look "reference" images were obtained and for all fields two second look "search" images were obtained $2-3$ weeks after the reference images. The images were flat-fielded and zero-points for the images were estimated by comparison with E (red) magnitudes of stars in the APM (Automated plate measuring facility, Cambridge, UK) POSSI catalog (McMahon & Irwin 1992). The search images were combined (after convolution to match the seeing of the worst of the four images) and the combined reference images were subtracted from this after scaling in intensity. The resulting difference image for each field was searched for SN candidates.

In this subset of the search data three SNe were found with redshifts 0.354, 0.375 and 0.420 determined from spectra of the host galaxies. For the purposes of this analysis, we assume these are all Type Ia SNe (see Perlmutter et al. 1996). The method used to calculate the rate can be divided into two main parts: (i) estimation of the number of galaxies and the total stellar luminosity (measured in $10^{10}\,L_{B\odot}$) to which the survey is sensitive and (ii) estimation of the SN detection efficiency and hence the control time.

2. Galaxy counts

In order to compare the distant SN rate with local equivalents, we need to know the redshifts of the galaxies we have surveyed. In this work we use the galaxy counts derived from the analysis of Lilly et al (1995) to estimate the number of galaxies sampled as a function of redshift. R band counts as a function of redshift were calculated by Lilly based on the analysis of magnitude–redshift data obtained in the Canada-France Redshift Survey

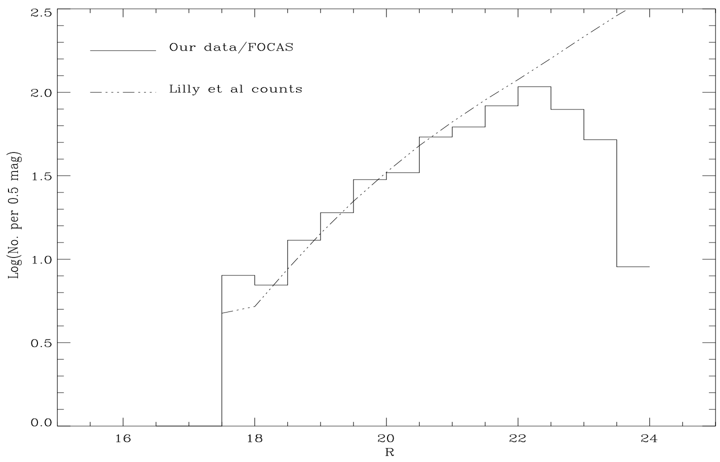

Figure 1. Number of galaxies as a function of magnitude determined from one of our non-cluster images using FOCAS. The dashed-dot line shows the counts derived from the analysis of Lilly et al (1995), integrated over the redshift range $0 < z < 2$, and normalized to the image area of 0.03 sq deg.

(Lilly et al, 1995 and references therein). To check that the assumed distribution of galaxies with R magnitude and redshift, $N(z, R)$, give reasonable galaxy counts compared to our data, we have plotted the number of field galaxies classified by the FOCAS software package, as a function of apparent magnitude, on one of the search images that was *not* targeted at a galaxy cluster. The R-band galaxy counts given by the analysis of Lilly et al (1995) integrated over the redshift range $0 < z < 2$ (dash-dotted line) are shown on the same scale, assuming an effective area for this image of 0.03 sq deg (Figure 1).

Many of our search fields were chosen specifically to target high-redshift clusters. For each of these fields, we estimate the number of cluster galaxies by counting galaxies as a function of R magnitude in a box of size 500×500 pixels centered approximately on the center of the cluster as estimated by eye from the images. The counts in a similar box in a region of the image away from the cluster were subtracted from the cluster counts to give the cluster excess counts as a function of R mag. Typically a cluster contributes 10% of the galaxy counts on an image. We assign these galaxies to the cluster redshift, and add the cluster contribution to the $N(z, R)$ for that image given by the models.

Values of reddening due to the Galaxy were supplied by D. Burstein (derived from Burstein & Heiles, 1982) for each field and applied to the data assuming $R_V = 3.1$ and $A_R/A_V = 0.751$ (Cardelli et al, 1989).

3. Control times and detection efficiencies

To calculate the control times we assumed that SN magnitude as a function of time follows the average of the best-fit, time-dilated and K-corrected Leibundgut (1988) Type Ia template light curves (the generalized K correction described by Kim et al. (1996) and Kim, Goobar & Perlmutter (1995), was used here). The control time is then given by the weighted sum of days during which the SN can be detected, where the weighting is by the detection efficiency, ϵ.

This detection efficiency is a function of the magnitude difference Δm (zero if Δm is negative), which is itself a function of time t relative to maximum, and δt, the time separation of the search and reference images. It depends on the quality of the subtracted images (seeing, transmission) together with the detailed technique (convolution, selection criteria) used to extract the signal (SNe candidates) from the background (cosmic rays, asteroids, bad subtractions, etc). In addition, there is a slight dependence on the host galaxy magnitude. The detection efficiency was calculated using a Monte-Carlo method. A synthetic image was created for every field by adding simulated supernovae to the search images using point-spread-functions drawn from each search image. The reference images were subtracted from the synthetic search images using exactly the same software as used for the supernova search and the number of simulated SNe that satisfy the selection criteria was determined. This technique allows us to measure detection efficiencies as a function of supernovae magnitude individually for every field, thus taking into account the other parameters mentioned above.

Figure 2(a)-(c) shows the fractional number of simulated SN recovered, as a function of SN magnitude (at detection) for the three fields in which SNe were found. Figure 2(d) shows the efficiency as a function of relative surface brightnesses of the SN and host galaxy. This last parameter gives an indication of the effect of SN location with respect to the host galaxy. Although this is a small effect, it was taken into account. For a typical field the detection efficiency is over 85% for any added fake stellar object brighter than $R = 22.0$ magnitude (Note that the more recent searches of this project have worked with significantly deeper images).

4. SN Ia Rates

4.1. SURVEY RATE

Before calculating the luminosity-weighted SN rate, we first determine a "survey rate" of SN discoveries that a search for Ia SNe can expect to obtain, per square degree. We give the rate in a range of 1 mag in R,

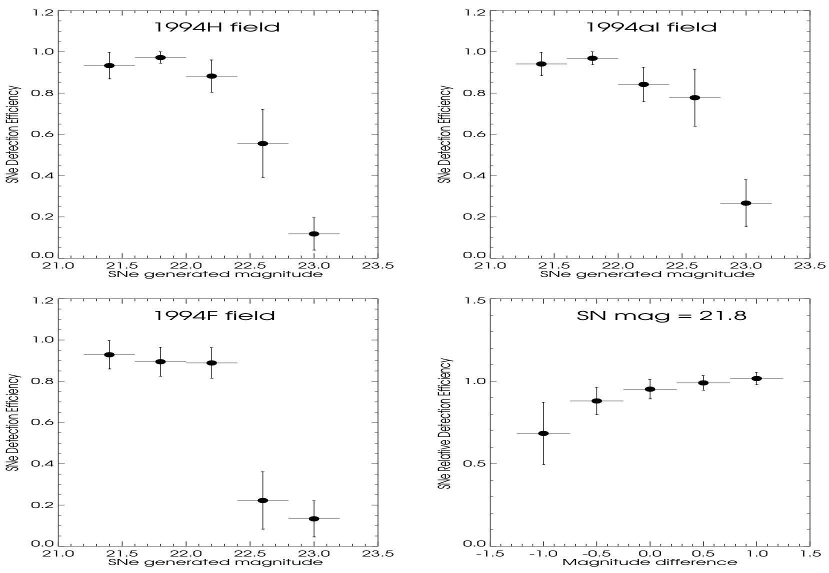

Figure 2. (a)-(c) Detection efficiency as a function of relative SN to host surface brightness. (d) Detection efficiency as a function of magnitude for the three difference images in which SNe were found. The vertical error bars show the 1σ statistical uncertainty, and the horizontal bars show the bin ranges.

centered on the mean peak R magnitude of the 3 SNe found in this search, $R = 21.8$. The survey rate is given by

$$survey\ rate\ (21.3 < R < 22.3) = \frac{N_{SN}}{\sum_i area_i \times \Delta T_i}.$$

where $N_{SN} = 3$ is the number of SNe we found in the 1 magnitude range, and ΔT_i is the control time for field i, computed for a SN with magnitude $R = 21.8$ at maximum. For example a value of $\Delta T_i = 21$ days was found for the field containing SN1994H observed on 1993 December 19 and 1994 January 12, 24 days apart. We measure a survey rate for $21.3 < R < 22.3$ of $34.4\ ^{+23.9}_{-16.2}$ SNe $year^{-1} deg^{-2}$ (the error quoted is statistical only). In practice this translates to 1.73 SNe per square degree discovered with a 3 week baseline, in data with limiting magnitude $R \sim 23$ ($S/N \sim 3$ for R=23).

4.2. RATE IN SNU

To calculate the rate in SNu, we compute the expected redshift distribution of SNe, $N_{exp}(z)$, which is proportional to the observed SN rate, $r_{SN}(1+z)^{-1}$,

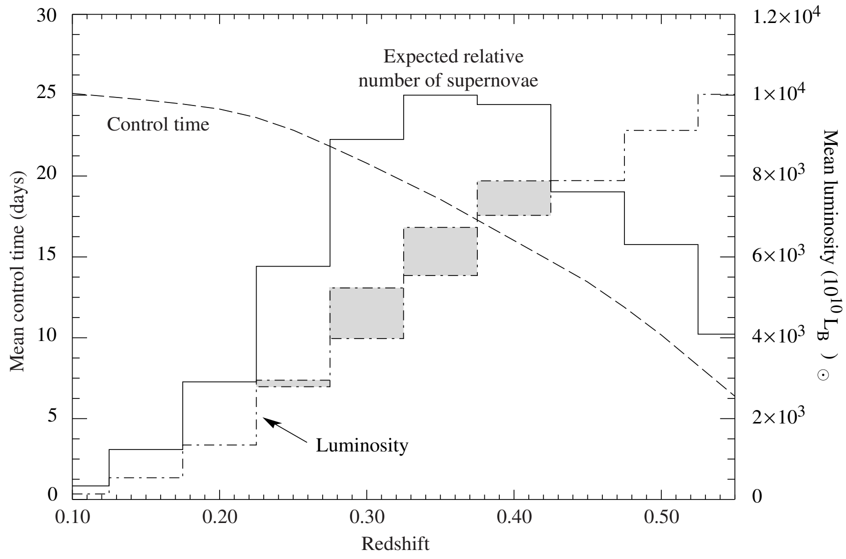

Figure 3. The expected number of supernovae as a function of z (solid histogram) together with the overall control time (dashed curve) and the luminosity-weighted number of galaxies (dash-dot histogram). The contribution to the luminosity from clusters is shown by the shaded area. The December 1993-January 1994 search data was most likely to find SNe with redshifts between $z = 0.3$ and $z = 0.4$. Between $z = 0.3$ and $z = 0.55$, the search was more than 50% efficient. Note that our more recent searches go deeper than this data.

where r_{SN} is the rate in the rest-frame of the supernovae. It is given by

$$N_{exp}(z) = \frac{r_{SN}}{1+z} \sum_R \sum_i N_{gal}(z,R)_i \times L_B(z,R) \times \Delta T_i(z,R)$$

where i runs over all fields, R is the galaxy apparent R magnitude and L_B is the galaxy rest-frame B band luminosity in units of $10^{10}\,\mathrm{L_{B\odot}}$. The control times ΔT, in units of centuries, have been calculated for each field in bins of z and R (the size of the bins is 0.5 mag in R, 0.05 in z).

To compute the rest-frame B band galaxy luminosities from apparent R magnitudes, we used $B - R$ colors and B-band K corrections supplied by Gronwall & Koo. Note that the combined color, K and evolution correction is small in the redshift range of interest $(0.3 - 0.5)$ since the observed R band is close to the rest-frame B-band. In this calculation $\mathrm{M_{B\odot}} = 5.48$ and $q_0 = 0.5$ were assumed. The rest frame supernovae rate r_{SN} at $z \sim 0.4$ was obtained by fitting the redshift distribution of observed SNe to the expected distribution, $N_{exp}(z)$ using a maximum-likelihood fit using Poisson statistics. The mean redshift corresponding to this rate is $< z >=$

TABLE 1. Systematic Uncertainties. Uncertainties in the rate are in h^2 SNu.

Source	uncertainty
Luminosity estimate	0.09
Cluster contribution	0.02
Galaxy extinction	0.01
APM calibration	0.10
Detection efficiency	0.08
non-standard SNe	0.29
Scanning efficiency	$-0.00 + 0.27$
Total syst. uncertainty	$-0.32 + 0.42$

0.38. We derive a value for the SN rate of

$$r_{SN}(z = 0.38) = 0.82\ ^{+0.54}_{-0.37}\ h^2 \text{ SNu}.$$

where the error is statistical only.

4.3. SYSTEMATIC UNCERTAINTIES

We have studied various sources of systematic uncertainty. Table 1 summarizes their contributions. For given assumed galaxy counts, the main contribution comes from the fact that Type Ia SNe are not perfect standard candles.

We also tested the sensitivity of our result to the assumed form of galaxy evolution, $N(z, R)$, by recalculating the rate using the model of Gronwall & Koo (1995) and that used by Glazebrook et al (1995). These give values for the rate of $1.61^{+1.05}_{-0.73} h^2$ SNu and $1.27^{+0.83}_{-0.57} h^2$ SNu respectively. Although there is a large difference in the results derived using the counts of Lilly et al compared with the other models, we choose not to include this in the systematic uncertainty. For the purposes of this analysis we use the Lilly et al counts, since these are based on data that are well-matched to our survey in magnitude and redshift range, and only small amount of extrapolation was required in converting from the I to R band.

Host galaxy inclination and extinction effects could not be estimated following the analysis used for nearby searches because of the different detection techniques involved. A correct estimation would require modeling of galaxy opacities, which is beyond the scope of this paper. We therefore compare our uncorrected value with uncorrected values for nearby searches, Altogether, we estimate the total systematic error to be $^{+0.32}_{-0.42}$ and we assume the Lilly et al counts for $N(z, R)$.

5. Discussion and Conclusion

This measurement is the first direct measurement of the Type Ia rate at high redshift. In their pioneering work searching for high redshift supernovae, Hansen et al. (1989) discovered a probable Type II event at $z = 0.28$ and a Type Ia event at $z = 0.31$ (Nørgaard-Nielsen et al., 1989), however no estimates of SN Ia rates were published based on this discovery.

Nearby Supernovae rates have been carefully reanalyzed recently (Cappellaro et al. 1993a & 1993b, Turatto et al., 1994, Van den Bergh and McClure, 1994, Muller et al. 1992) using more precise methods for calculating the control times and correcting for inclination and over-exposure of the nuclear regions of galaxies in photographic searches. The rate obtained for Type Ia SNe are now consistent among these groups and vary between 0.2 h^2 SNu and 0.7 h^2 SNu depending on the galaxy types (E, Sa etc., higher rates are found in later type galaxies). Taking into account the facts that at $z \sim 0.4$ the ratios of galaxy type are different and using the Type Ia rates reported in Cappellaro et al (1993b), we calculate a local rate of 0.53 ± 0.25 h^2 SNu for the mix of galaxies expected at $z \sim 0.4$. Our measured value of $0.82^{+0.68}_{-0.49} h^2$ SNu (where statistical and systematic uncertainties have been combined), although slightly higher, agrees with this value within the uncertainty and indicates that Type Ia rates do not change dramatically out to $z \sim 0.4$. Note, however that correcting for host galaxy extinction and inclination may change this conclusion.

Theoretical estimates of Type Ia SNe rates have been derived from stellar and galaxy evolution models. Calculations were done mostly for elliptical galaxy type. Recent calculations, based on evolutionary models of elliptical galaxies, predict rates of $\sim 0.1 h^2$ SNu (Ferrini & Poggianti 1993). Assuming a factor of ~ 2 higher rate in non-elliptical galaxies compared to ellipticals (Capellaro et al. 1993b) and a mix of galaxy types as above, we convert this to an overall rate of Type Ia SNe at $z \sim 0.4$ in all galaxy types, and derive a value of $\sim 0.37 h^2$ SNu. Our total uncertainty of $^{+0.68}_{-0.49}$ in the measurement presented in this paper does not allow any firm conclusion but our observed rate seems to lie above this theoretical prediction. There may be an increase of Type Ia rate with redshift. Ruiz-Lapuente, Burkert & Canal (1995) predict significant increase in rate for redshifts between 0.4 and 0.8 depending on the specific model they consider. In the near future, our ongoing high-z SN search and others should provide enough data to constrain the theoretical calculations.

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