The Distant Type Ia Supernova Rate

S. Fabbro, on behalf of the Supernova Cosmology Project (SCP)
LPNHE IN2P3/CNRS, 4, place Jussieu F75252 Paris cedex 05

We report on a measurement of the rate of distant Type Ia supernovae. The result is derived using 4 large subsets of data from the Supernova Cosmology Project. Thirty-eight supernovae were detected at redshifts 0.25–0.85 in a surveyed area of about 12 square degrees. The survey spanned a ~ 3 week baseline and used images with 3σ limiting magnitude ranging from $R = 22.5$ to $R = 24.5$. Preliminary values for the rest-frame rates per unit volume and per unit luminosity are presented.

1 Introduction

In a previous paper [5], hereafter Paper I, we presented the first measurement of the type Ia supernovae (SNe Ia) rate at high redshift, based on 3 SNe Ia discovered in 1994 at the 2.5 meter Isaac Newton Telescope. We report here on a new measurement of the distant SN Ia rate based on 38 SNe Ia at redshifts 0.25–0.85 discovered during 4 observing runs at the Cerro Tololo 4-meter telescope.

The method used to calculate the SNe rate was described in detail in Paper I. It can be divided into two main parts: (i) estimation of the SN detection efficiency and hence the "control time," the effective time during which the survey is sensitive to a Type Ia event and (ii) estimation of the volume and the total stellar luminosity (measured in $10^{10}\,L_{B\odot}$) to which the survey is sensitive. In this paper, we compute the rate per unit volume ($Mpc^{-3}\,yr^{-1}$) and the rate per unit luminosity (SNu = SN per century per $10^{10}\,L_{B\odot}$).

2 The Data Sets

For this analysis, we have studied 4 sets of respectively 68, 46, 61 and 44 similar search fields giving a total of about 12 square degrees. These fields were observed in November and December 1995 for the first set (Set A), in February and March 1996 for the second set (Set B), in

February and March 1997 for the third set (Set C) and in November and December 1997 for fourth one (Set D), using the Cerro Tololo 4-meter telescope in Chile.

These data sets were obtained as part of the search for high-redshift supernovae the Supernova Cosmology Project. For all fields, first-look "reference" images were obtained, and second look "search" images were obtained $2-3$ weeks after the reference images. The useful area of this dataset is defined by the overlap area of the original set of reference images with search images. The total useful area covered in this study is ~ 12 square deg.

The original search for supernovae was done in view of measuring the cosmological parameters Ω_M and Ω_Λ [6]. For the purpose of measuring the rate, a completely new analysis was performed on the same images, slightly raising the main signal-to-noise ratio cut (typically to 5σ) when searching for candidates in order to get good control of the supernova detection efficiencies. Altogether, thirty-eight SNe with redshifts ranging from 0.25 to 0.85 were retained. All but one of these supernovae had been observed spectroscopically using the Keck telescope. They were all identified as or consistent with being of Type Ia. The redshifts were determined from spectra of the host galaxies. The remaining candidate had not been followed-up spectroscopically due to lack of telescope time. Its lightcurve however indicates that it is consistent with a type Ia SN at redshift $z \sim 0.7$. We therefore also retained this object for the purposes of this analysis.

3 Detection efficiency and Control Time

We followed the procedure described in Paper I to calculate the Control Times and detection efficiencies. The detection efficiencies depend primarily on the supernova magnitude but the Monte-Carlo calculation allows also to take into account the small dependence on the relative supernova to host surface brightness. We reached significantly fainter detection limits during these observations as compared to the data in[5]. Figure 3 shows the fractional number of simulated SNe recovered, as a function of SN magnitude (at detection) for 12 of the 219 fields observed. For a typical field the detection efficiency is over 85% for any stellar object brighter than $R = 23.5$.

4 SN Ia Rates per unit volume

To calculate the rate per unit volume, we derive the expected redshift distribution of SNe, $N_{exp}(z)$, which is proportional to the observed SN rate, $r_V(1+z)^{-1}$, where r_V is the rate in the rest-frame of the supernovae per unit volume. The expected distribution is given by

$$N_{exp}(z) = \frac{r_V}{1+z} \sum_R \sum_i S_i \times V(z; \mathrm{H}_0, \Omega_\mathrm{M}, \Omega_\Lambda) \times \Delta T_i(z, R_{gal}) \quad (1)$$

where i runs over all fields, S_i is the field area and $V(z)$ is the comoving volume element at redshift z (formally dV/dz/dS) which depends on the cosmological parameters H_0, Ω_M and Ω_Λ (see for example [1]). Note that the sum runs over all possible galaxy apparent R_{gal} magnitudes, since the control times, ΔT depend also on this quantity. These control times have been calculated for each field in bins of z and R (the size of the bins used is 0.5 mag in R, 0.1 in z).

Assuming a constant rate as a function of redshift, we fit the observed redshift distribution to N_{exp} and hence derive r_V at a mean redshift, $\bar{z} = \int z N_{exp}(z) dz / \int N_{exp}(z) dz$. The dependence of r_V on the Hubble parameter H_0 is easily factorized since the volume element scales as H_0^{-3} but the rate per unit volume also depends strongly on the cosmological parameters, Ω_M and Ω_Λ. We therefore provide the result as a function of $h = \mathrm{H}_0/100$ and for a flat cosmology with

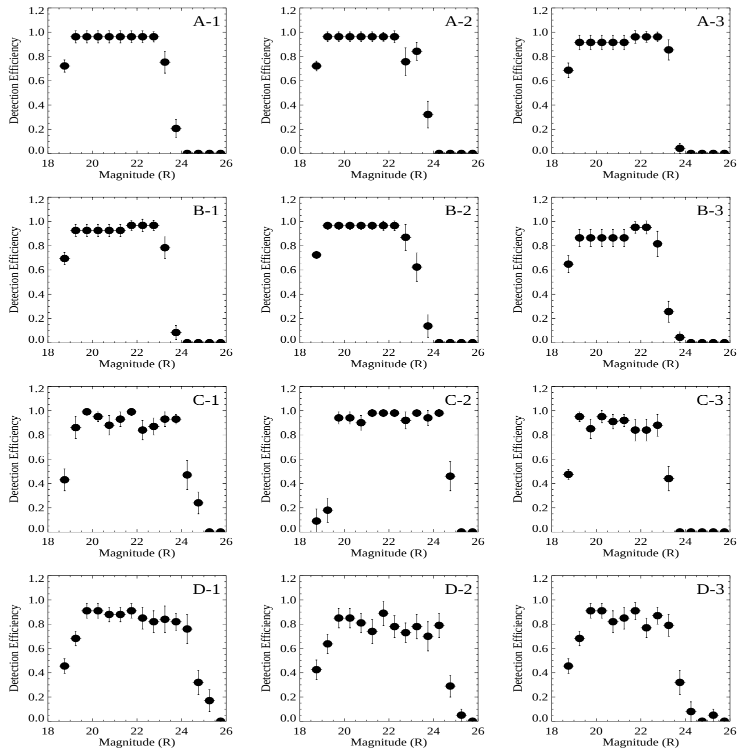

Figure 1: Detection efficiency versus R magnitude for 12 of the 219 $2k \times 2k$ fields that were searched for supernovae. 1995as, 1996cj, 1997ai and 1997ep were respectively discovered on fields A-1, B-1, C-1 and D-1.

$\Omega_{\rm M} = 0.3$ and find :

$$r_V(\bar{z} = 0.54) = [1.65^{+0.28}_{-0.25}(stat.)]h^3\ 10^{-4}\ \ Mpc^{-3}\ yr^{-1}$$

5 SN Ia Rates per unit galaxy luminosity

To compare the distant SNe rate with local rate, it is convenient to express the rate in SNu, the number of SNe per century per 10^{10} solar luminosities in the rest-frame B band. For that, we proceed as described in Paper I and calculate the expected redshift distribution of type Ia SNe given by

$$N_{exp}(z) = \frac{r_L}{1+z} \sum_R \sum_i N_{gal}(z,R)_i \times L_B(z,R;\mathrm{H}_0,\Omega_{\rm M},\Omega_\Lambda) \times \Delta T_i(z,R)$$

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} $\mathrm{L}_{\mathrm{B}\odot}$which depends upon the cosmological parameters H_0, $\Omega_{\rm M}$ and Ω_Λ.

Since thousands of anonymous high-redshift galaxies are observed in each image, it is more difficult than for nearby SN searches to estimate the number, morphological type and luminosity of galaxies searched in a given redshift range. We have computed the B band galaxy luminosity as in Paper I. In these calculations $\mathrm{M}_{\mathrm{B}\odot} = 5.48$ was used and the effect of H_0, $\Omega_{\rm M}$ and Ω_Λ is fully taken into account. R band counts as a function of redshift were used following S. Lilly[4] based on the analysis of I band magnitude–redshift data obtained in the Canada-France Redshift Survey ([3] and references therein). Since the I band is close to the R band, and the magnitude range of the CFRS sample is comparable to that of our data, the extrapolation is small

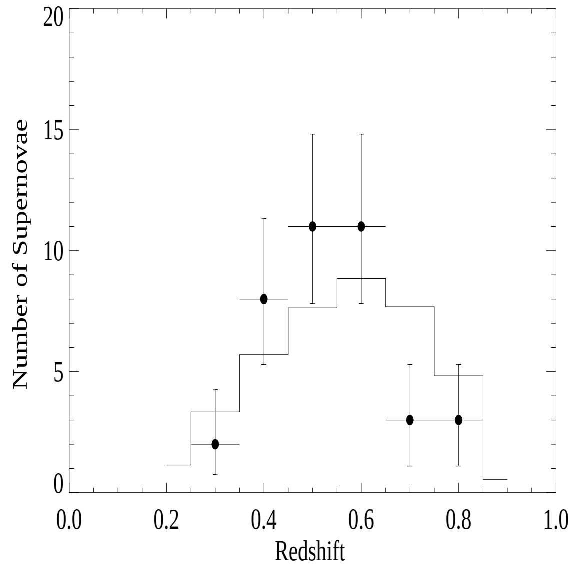

Figure 2: Rate per unit luminosity: Comparison of Monte-Carlo (histogram) and data (points) for the observed number of supernovae as a function of redshift. The prediction assumes that the rate follows the galaxy luminosity evolution as a function of redshift. A value of $0.65\ h^2$ SNu is taken for the rate and $\Omega_{\rm M} = 0.3$ and $\Omega_\Lambda = 0.7$ is used.

and the dependence of R band counts on the cosmological parameters is negligible. To compute the rest-frame B band galaxy luminosities from apparent R magnitudes, we used $B - R$ colors and B-band K corrections provided by C. Gronwall[2].

The type Ia supernovae rate per unit luminosity has then been derived using this estimate for the B-band total galaxy luminosity and assuming that the rate per unit luminosity is constant as a function of redshift. For a flat Universe with $\Omega_{\rm M} = 0.3$, we find :

$$r_L(\bar{z} = 0.54) = [0.62^{+0.10}_{-0.09}(stat)]\ \ h^2\ \ SNu$$

6 Systematic uncertainties

With a total of almost forty SNe, the statistical uncertainty becomes small enough that a very careful analysis of systematic uncertainties has to be performed. We have estimated the systematic uncertainties coming from detection efficiency, field calibration, cluster contribution, Galaxy extinction and the range of type Ia lightcurves used in the Monte-Carlo simulations. For the rate per unit luminosity systematics from calculating the luminosity was also estimated. Overall, the total systematic uncertainty is estimated to be $\pm 0.24 h^3 Mpc^{-3} yr^{-1}$ for the rate per unit volume and $\pm 0.10 h^2 SNu$ for the rate per unit luminisity, for a flat Universe with $\Omega_{\rm M} = 0.3$.

References

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