

The Evolution of the Cosmic Supernova Rates

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Scientific category: SUPERNOVAE
Instruments: NIR/CAM, NIR/SPEC, NIR/MSPEC
Days of observation: 0

Abstract

Through a combination of deep wide-field imaging and near-IR spectroscopy, the NGST will be able to chart with unprecedented accuracy the evolution of cosmic structures after the ‘dark ages’ ($z \lesssim 5$), when galaxies are thought to assemble and form the bulk of their stars. In particular, accurate measurements at all redshifts of the frequencies of Type II and Ia SNe could be used as a probe of the star formation and heavy element enrichment history of the universe, and improve our understanding of the intrinsic nature and age of the populations involved in SN explosions. The deep imaging programs targeted at field galaxies and gravitational lenses will find of order 20 Type II SN per 4×4 arcmin² field per year in the redshift range $2 < z < 5$ (at peak brightness). The derived SN II number counts in the JKLM bands for SCDM and LCDM cosmological models show that NGST will be able to detect 75% - 50% (respectively) of the supernovae occurring up to $z = 15$ in the J band. Follow-up spectroscopy at $R = 300$ for 200 candidates at $AB = 28 - 29$ mag will provide an adequate sample for constraining the nature of Type Ia progenitors and the evolution of the stellar birthrate in the Universe.

ASWG DRM Proposal
The Evolution of the Cosmic Supernova Rates

Observing Summary:

Target	RA	Dec	K_{AB}	Configuration/mode	Days
	N/A	N/A		NIR/SPEC	0
				Grand total days	0

NOTE: The search for SNe is a by-product of the deep galaxy and gravitational lens surveys that are also part of the DRM.

■ Scientific Objectives

Supernova are emerging as a highly valued probe of the distant universe in addition to the more traditional use of faint galaxies. The evolution of the SN rate with redshift, in particular, contains unique information on the star formation history of the universe, the initial mass function (IMF) of stars, and the nature of the binary companion in Type Ia events. All are essential ingredients for understanding galaxy formation, cosmic chemical evolution, and the mechanisms which determined the efficiency of the conversion of gas into stars in galaxies at various epochs.

While the frequency of core-collapse SN II, which have short-lived progenitors (e.g. Wheeler & Swartz 1993), is essentially related, for a given IMF, to the instantaneous stellar birthrate of stars with $M > 8 M_{\odot}$, Type Ia SNe – which are believed to result from the thermonuclear disruption of C-O white dwarfs (WDs) in binary systems – follow a slower evolutionary clock, governed by the lifetime of the primary star and the time taken for a non-degenerate companion to fill its Roche lobe (or, in the case the companion is another WD, the orbital decay time following gravitational wave emission). The evolution of Type Ia SN rate depends then, among other things, on the unknown mass distribution of the secondary binary components or on the distribution of the initial separations of the two WDs (Branch et al. 1995; Ruiz-Lapuente et al. 1997; Yungelson & Livio 1998). Thus the SN Ia rate at high redshift is not only sensitive to the *past* stellar birthrate but also to the nature of the event itself.

Figure 1 shows the predicted redshift dependence of Type Ia and II rest-frame frequencies per unit comoving volume for two different cosmic star formation histories, both able to account for the entire optical background light as recorded in the galaxy counts (Madau et al. 1998b). Because of the uncertainties in the amount of starlight that was absorbed by dust and reradiated in the far-IR at early epochs, however, these numbers should be taken as indicative and used for the purpose of illustration only. Our estimates are probably rather conservative, as the model produces only a fraction $\sim 50\%$ of the IR background detected by COBE (Dwek et al. 1998). Note that the rate of SN II closely tracks the stellar birthrate of massive stars. The Type Ia rates assume characteristic “delay” timescales after the collapse of the primary star to a WD equal to $\tau = 0.3, 1$ and 3 Gyr, which virtually encompass all relevant possibilities. The SN Ia explosion efficiency was left as an adjustable parameter to reproduce the observed ratio of SN II to SN Ia explosion rates in the local universe, $R_{\text{II}}/R_{\text{Ia}} \approx 3.5$, and is between 5 and 10% for the adopted models.

A determination of the amount of star formation at early epochs may be of crucial importance, as it is possible that the two competing scenarios for galaxy formation, monolithic collapse – where spheroidal systems formed early and rapidly, experiencing a bright starburst phase at high- z (Eggen et al. 1962; Tinsley & Gunn 1976) – and hierarchical clustering – where ellipticals form continuously by the merger of disk/bulge systems (White & Frenk 1991; Kauffmann et al. 1993) and most galaxies never experience star formation rates in excess of a few solar masses per year (Baugh et al. 1998) – make rather different predictions in this regard. In the context of hierarchical models, detailed predictions can be made on the

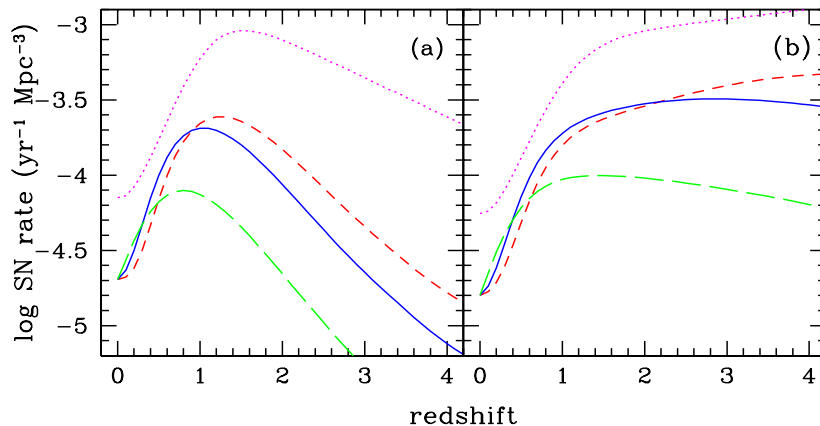


Figure 1: *SN rest-frame frequencies as a function of redshift from the models of Madau et al. (1998a). Dotted line: SN II rate. Short-dashed line: SN Ia rate with $\tau = 0.3$ Gyr. Solid line: SN Ia rate with $\tau = 1$ Gyr. Long-dashed line: SN Ia rate with $\tau = 3$ Gyr. (a) Model predictions for a scenario where the bulk ($\gtrsim 60\%$ by mass) of the stars present today formed relatively recently ($z \lesssim 1.5$). (b) Same for a scenario in which half of the present stars were formed at $z > 2.5$.*

evolution of expected SN rate from semianalytical models of galaxy formation based on the Press-Schechter formalism (Marri, Ferrara & Pozzetti 1999). The derived rates are broadly consistent with the ones derived from the observed star formation history up to $z \approx 4$ and shown in Figure 1, but typically the peak occurs at higher redshifts ($z \simeq 3 - 4$) both for SCDM ($\Omega_M = 1, \Omega_\Lambda = 0, \sigma_8 = 0.57$) and LCDM ($\Omega_M = 0.4, \Omega_\Lambda = 0.6, \sigma_8 = 0.95$).

By detecting Type Ia and Type II SNe at high- z , NGST should provide an important test for distinguishing between different scenarios of galaxy formation.

■ NGST Uniqueness/Relationship to Other Facilities

In the interval $0 \lesssim z \lesssim 1$, the predicted rate of SN Ia is a sensitive function of the characteristic delay timescale between the collapse of the primary star to a WD and the SN event. Accurate measurements of SN rates in this redshift range will improve our understanding of the nature of SN Ia progenitors and the physics of the explosions. Ongoing searches and studies of distant SNe should soon provide these rates, allowing a universal calibration of the Type Ia phenomenon.

While Type Ia rates at $1 \lesssim z \lesssim 2$ will offer valuable information on the star formation history of the universe at earlier epoch, the full picture will only be obtained with statistics on Type Ia and II SNe at redshifts $2 < z < 4$ or higher. At these epochs, the detection of Type II events must await the NGST. A SN II has a typical peak magnitude $M_B \approx -17$ (e.g. Patat et al. 1994): placed at $z = 3$, such an explosion would give rise to an observed flux of 15 nJy (assuming a flat cosmology with $q_0 = 0.5$ and $H_0 = 50 h_{50} \text{ km s}^{-1} \text{ Mpc}^{-1}$) at $1.8 \mu\text{m}$.

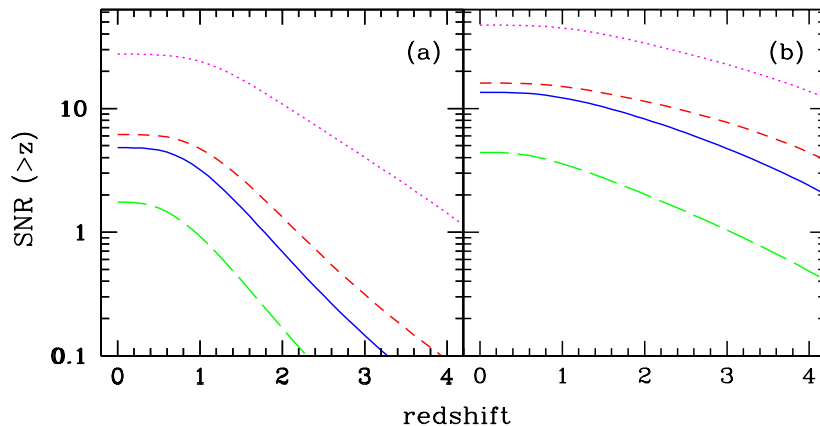


Figure 2: *Predicted cumulative number of Type Ia and II(+Ib/c) SNe above a given redshift z in a $4' \times 4'$ NGST field. Dotted line: Type II's. Short-dashed line: Type Ia's with $\tau = 0.3$ Gyr. Solid line: Type Ia's with $\tau = 1$ Gyr. Long-dashed line: Type Ia's with $\tau = 3$ Gyr. The effect of dust extinction on the detectability of SNe has not been included in the models. (a) Model predictions for the merging scenario of Figure 1a. (b) Same for the monolithic collapse scenario of Figure 1b.*

At this wavelength, the imaging sensitivity of an 8m NGST is 1 nJy (10^4 s exposure and 10σ detection threshold), while the moderate resolution ($\lambda/\Delta\lambda = 1000$) spectroscopic limit is about 50 times higher (10^5 s exposure per resolution element and 10σ detection threshold) (Stockman et al. 1998). The several weeks period of peak rest-frame blue luminosity would be stretched by a factor of $(1+z)$ to few months. Figure 2 shows the cumulative number of Type II events (at peak brightness) expected per year per $4' \times 4'$ field. Depending on the history of star formation at high redshifts, the NGST could detect between 7 (in the merging model) and 15 (in the monolithic collapse scenario) Type II SNe per field per year in the interval $2 < z < 4$. The possibility of detecting Type II SNe at $z \gtrsim 5$ from an early population of galaxies has been investigated by Miralda-Escudé & Rees (1997), Marri & Ferrara (1998), and Marri, Ferrara & Pozzetti (1999). By assuming these are responsible for the generation of all the metals observed in the Lyman- α forest at high redshifts, a high baryon density ($\Omega_b h_{50}^2 = 0.1$), and an average metallicity of $0.01Z_\odot$, Miralda-Escudé & Rees estimate that NGST should observe about 16 SN II per field per year with $z \gtrsim 5$. Note, however, that a metallicity smaller by a factor ~ 10 compared to the value adopted by these authors has been recently derived by Songaila (1997). For comparison, the models discussed here predict between 1 and 10 Type II SNe per field per year with $z \gtrsim 4$.

Marri, Ferrara & Pozzetti have derived SN II number counts for $0 \leq z \leq 15$ in the JKLM bands appropriate to the planned sensitivity range of NGST for SCDM and LCDM models (with parameters given above). They simulate the observation of 80 NGST fields, $4' \times 4'$ each, i.e. 0.35 deg^2 , surveyed for one year; this experiment is well within the scheduled observational plans and capabilities of NGST (Stockman et al. 1998). From the rates

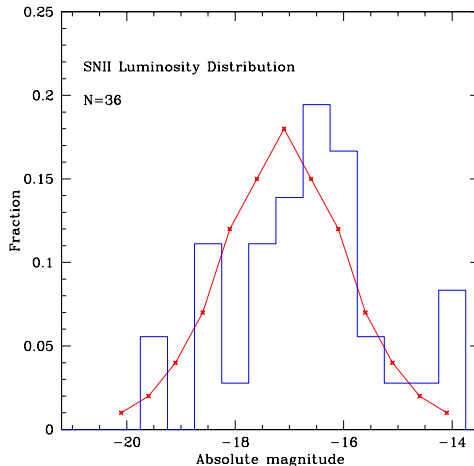


Figure 3: *Local luminosity function for Type II SNe. histogram: Patat et al. (for 36 SN II); solid line: Van den Bergh & McClure.*

predicted by these models, the expected number of SN II in the above cosmic volume has been obtained, and a peak luminosity to each SN II assigned by randomly sampling the local SN II luminosity function (assuming no evolution). The latter quantity has been taken from Patat et al. (1994) who conclude that SN II seem to cluster in at least three groups, which they classify according to their B-mag at maximum as *Bright* ($\langle M_B \rangle = -18.7$), *Regular* ($\langle M_B \rangle = -16.5$), and *Faint* ($\langle M_B \rangle = -14$), respectively. Note that the Faint class is constituted by a single object, i.e. SN1987A. This classification is based on a limited sample (about 40 SN II), and therefore a statistical bias cannot be ruled out. Patat et al. results are also compatible with the empirical distribution law given by van den Bergh & McClure (1994); both distributions are shown in Figure 3. Assuming a black-body spectrum, $B_\nu(T)$, at a temperature $T = 25000$ K approximately $15(1+z)$ days after the explosion (Kirshner 1990, Woosley & Weaver 1986), negative K -corrections (≤ -4 for $z \geq 4$) allow to detect SN II in the above bands at high- z . We have taken into account absorption by IGM (Madau 1995), which affects J number counts for $z \gtrsim 9$.

Figure 4 shows the differential SN II counts $N(m)$ [$0.5 \text{ mag/yr}/0.35 \text{ deg}^2$] as a function of AB magnitude. The four panels contain the curves for the SCDM and LCDM models in the J, K, L, and M bands. For comparison, we plot the NGST magnitude limit $AB = 31.4$ (vertical line), corresponding to the imaging sensitivity for an 8m mirror used above. NGST should be able to reach the peak of the expected SN II count distribution, which, for the SCDM model, is located at $AB \approx 30 - 31$ (depending on the model and wavelength band). The differences among the various bands are not particularly pronounced, although J and K bands present a larger number of luminous ($AB \leq 27$) sources, and therefore might be more suitable for the experiment. The two cosmological models (SCDM, LCDM) predict a total number of (617, 2654) SN II/yr in 80 NGST fields in $0 \leq z \leq 15$, of which a fraction

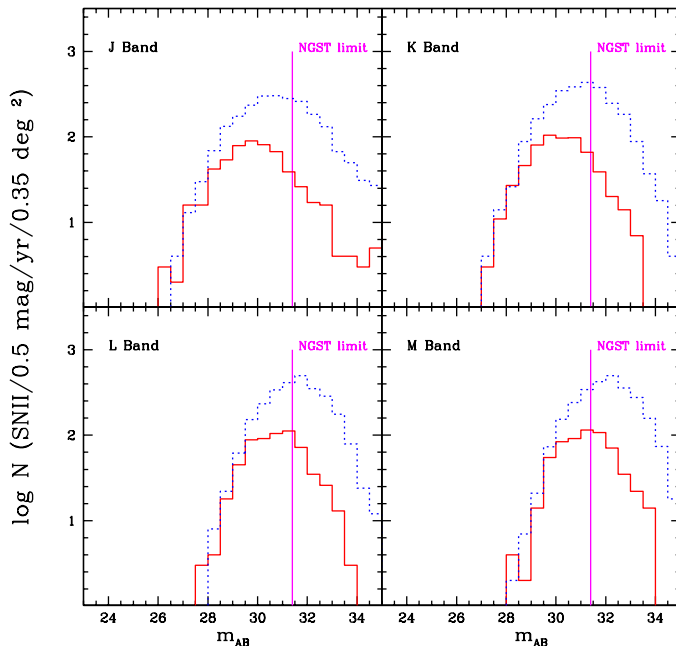


Figure 4: *Differential number counts for the two cosmological models considered as a function of apparent AB magnitude in J, K, L, M bands (SCDM: solid line, LCDM: dotted). Also shown is the NGST imaging sensitivity limit.*

\approx (75%, 50%) can be above the detection threshold of NGST in the J band. These numbers are only slightly modified by the inclusion of cosmological gravitational lensing effects (Marri, Ferrara & Pozzetti 1999).

From these results it is evident that by pushing SN II searches to faint magnitudes, we will be able to build a statistically significant sample, which will allow to test various cosmological models and study the cosmic star formation history of the universe at epochs otherwise difficult to investigate.

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■ Observing Strategy

See complementary DRM proposal on measuring cosmological parameters with high- z SNe.

■ Special Requirements

■ Precursor/Supporting Observations

From Figure 1 it appears that observational determinations of the SN Ia rate at $z \sim 1$ could unambiguously identify the appropriate “delay” time. In particular, measuring the frequency of Type Ia events at both $z \sim 0.5$ and $z \sim 1$ with an error of 20% or lower would allow one to determine this timescale to within about 30%. This kind of observations are by no means prohibitive, and these goals could be achieved within the next few years. In fact, ongoing searches for high- z SNe (Perlmutter et al. 1998; Garnavich et al. 1998) are currently able to discover and study about a dozen new events per observing session in the redshift range 0.4-1.0, and the observations are carried out at a rate of about four sessions a year. Since determining the frequency of SN Ia with a 20% uncertainty requires statistics on more than 25 objects per redshift bin, it is clear that, barring systematic biases, those rates might soon be known with good accuracy. Therefore, once such timescale is calibrated through the observed ratio $R_{\text{Ia}}(z=0)/R_{\text{Ia}}(z=1)$, one should be able to use NGST to constrain the star formation history of the early universe by comparing the predicted SN Ia rate at $z > 2$ with the observations.