Estimating Starburst Supernova Rates Using OSSE Observations of M82 and NGC 253

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Abstract

We have used the OSSE observations of the starburst galaxies NGC 253 and M82 to obtain upper limits to the Type Ia and Ib supernova rates in these galaxies. Monte Carlo simulations of randomly occurring supernova events in NGC 253 and M82 were performed to evaluate the significance of our upper limit to the 0.847 and 1.238 MeV ^{56}Co gamma-ray line fluxes on the supernova rate from these two galaxies. A set of observations of NGC 253 and M82 by OSSE is suggested in order to maximize the chances of gamma-ray line detection from these sources.

1. Introduction

Intial observations of the starburst galaxies in radio and infra-red wavelengths suggested that these galaxies have a high supernova rate - on the order of 0.1 - 0.3 yr^{-1}. This inference was deduced based on the radio observations of supernova remnants in M82 where some remnants apparently showed remarkable decrease in intensity within 6 months (Kronberg, Biermann and Schwabb 1985). However, recent radio observations of Ulvestad and Antonucci (1993) of M82 and NGC 253 suggest that the variability in the source intensity may result due to the differences in calibrations and measurements and hence, the rates in these galaxies may not be as high as claimed before. The radio rates are based only on the observations of Type II supernova remnants. Type Ia SNRs are not detected in radio, whereas Type Ib are detected only for a short time. Type Ib radio supernovae have a steeper spectra and rapid decay than Type IIs (Weiler and Sramek, 1988). Using the relative extragalactic supernova frequencies given by Van den Bergh and Tammann (1991) and a Hubble constant of 100 km s^{-1} Mpc^{-1} we find for NGC 253 (a type Sc galaxy) SN rates of 1, 1.5 and 7.5 per century for Types Ia, Ib and II, respectively (we should note that had we used a Hubble constant of 50 km s^{-1} Mpc^{-1} the

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rates would drop by a factor of 4). The total supernova rate 10 per century is consistent with the rate deduced by Ulvestad and Antonucci, although our estimation does not take into account the starburst nature of NGC 253. A rate of < 0.1 sn yr-1 results in agreement with one of the starburst models (D) of Rieke et al. (1980) which correctly predicts the bolometric luminosity, but underpredicts the radio intensity by an order of magnitude.

Most of the supernovae in starburst galaxies will not be detectable in optical wavelengths due to the presence of dust in the starburst cores. Hence, it is not clear whether for an infra-red bright galaxy such as NGC 253, the ratio N(Type II)/N(Type Ia + Type Ib) ~ 3 would hold. It is generally believed that only population II stars produce Type Ia SNe so that such events are unlikely to occur in starburst cores. However, due to the present insufficient knowledge of the Type Ia progenitors we do not preclude the possibility that Type Ia may come from a wide variety of population. Indeed, the observations that SN Type Ia rate per unit infra-red luminosity is an order of magnitude higher in Sc spirals than it is in E and So type galaxies may indicate that not all SN Ia are associated with a very old stellar population (Van den Bergh 1990). In this respect gamma-ray observations of starburst galaxies may serve a promising role with its potential to detect supernovae signatures through the dense starburst nuclear regions and complement the radio observations. Such observations could be used as a direct estimator of supernova rates and discern between different types of SNe occuring in the starburst cores. Some of the starburst galaxies are sufficiently nearby so that supernovae lines of Type Ia, Ib and Ic may be detected at a significant level. The recent detection of supernova continuum from SN 1993J from M81 (which is a companion galaxy of M82) by OSSE proves that it is not unreasonable to expect detectable Type I supernovae in gamma-rays from these nearby infrared luminous galaxies.

2. Observations and Results

OSSE observed NGC 253 during 4 viewing periods and M82 during 5. The target for the last three M82 VP's was actually M81, but due to the close proximity of these two galaxies (~1_) OSSE field-of-view could not distiguish between them. The VPs are given in Table 1. Upper limits to the NGC 253 and M82 847 keV lines are given in Table 2. The detailed results are presented elsewhere (Bhattacharya 1993, Lihsin 1993, Leising 1993). During the first three VPs NGC 253 was detected up to 200 keV with a total significance of 4.2σ and an estimated luminosity of $3 \infty 10^{40}$ ergs s-1. The spectrum is best fit by a photon power law index of ~ 2.5. A search for gamma-ray lines from the decay of the most abundant radioactive element produced in the supernovae($^{56}Ni\varnothing^{56}Co\varnothing^{56}Fe$) yielded no significant detection: the 3σ upper limits at 0.158, 0.847 and 1.238 MeV are $4 \infty 10^{-5}$, $8 \infty 10^{-5}$ and $9 \infty 10^{-5}$ cm^{-2} s^{-1}, respectively. The last VP of NGC 253 showed no significant continuum emission. No significant continuum flux was observed from from M82. The 3σ upper limits of 0.847 MeV ^{56}Co gamma-line fluxes are $2.2 \infty 10^{-4}$ and $1.2 \infty 10^{-4}$ cm^{-2}s^{-1}, respectively.

3. Supernova Rates

Based on the non-detection of supernovae lines and Monte Carlo simulations we have ascertained upper limits to the supernova rates in these galaxies. Monte Carlo simulations of randomly occurring supernova events in NGC 253 and M82 were performed to evaluate the significance of our upper limit to the 0.847 and 1.238 MeV ^{56}Co gamma-ray line fluxes on the supernova rate from these two galaxies. For this purpose we take the 3σ upper limit to be the best-fit value plus three standard deviations from that value, even though this confidence limit may differ slightly from the expected 3σ sensitivity of OSSE to lines. The 3σ upper limits to the 0.847 MeV gamma-line fluxes from first two viewing periods of M82 and the first three viewing periods of NGC 253 were compared with the line flux generated by the Monte Carlo histories. The fraction of galaxies in the simulations that would be fainter than both 3σ OSSE limits at 847 keV is shown in figure 1. It therefore represents the prob-

VP 9: f847 3σ upper limit = 1.90×10^{-4} γ/cm²/sec   VP 7: f847 3σ upper limit = 2.32×10^{-4} γ/cm²/sec
VP 13 & 16: f847 3σ upper limit = 1.10×10^{-4} γ/cm²/sec   VP 18: f847 3σ upper limit = 1.52×10^{-4} γ/cm²/sec

W7 0.58 $M_\odot$ ^{56}Ni
W7 f_{escp}=1
WR6Cfm 0.16 $M_\odot$ ^{56}Ni
WR6Cfm f_{escp}=1
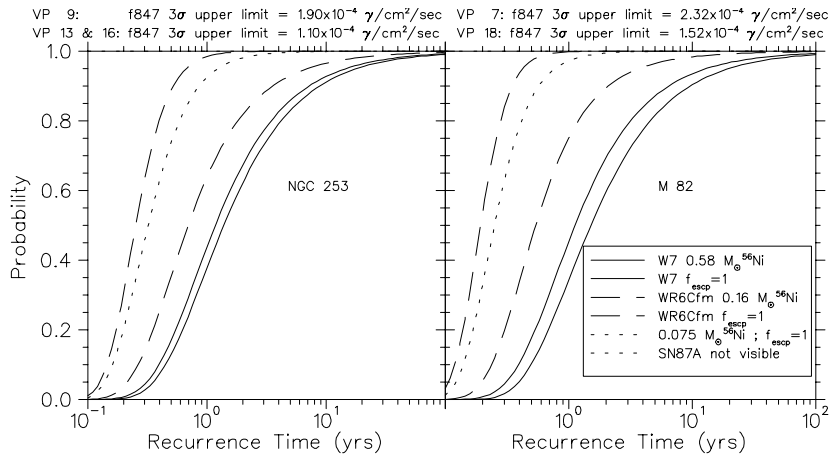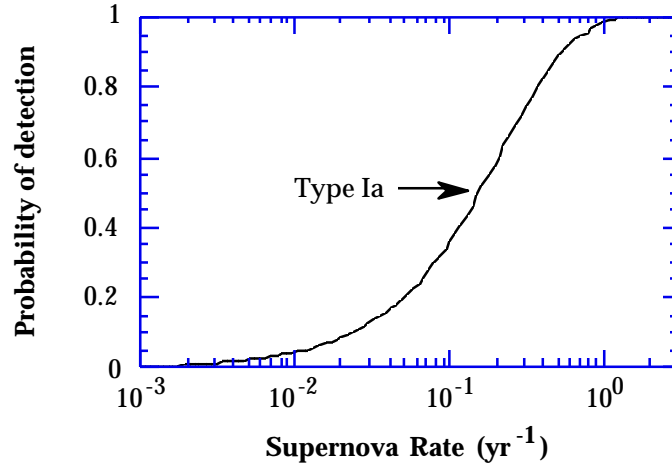0.075 $M_\odot$ ^{56}Ni ; f_{escp}=1
SN87A not visible

Fig. 1 The probability for the 847 keV gamma-line fluxes from stohastically occuring Type Ia, Type Ib, and Type II supernovae to be less than both 3σ upper limits a) for the three NGC 253 observations, and b) for the two M82 observations.

ability that that particular astrophysical simulation would not have been detected. Different types of supernova models are used in the simulation but are considered independently of each other. Model W7 is a Type Ia supernova deflagration model of carbon-oxygen white dwarf thermonuclear explosion (Nomoto, Thielemann and Yokoi 1984).WR6C is a Type Ib supernova model of Wolf-Rayet progenitor (Ensman and Woosley 1988). For Type II supernova we take the SN87A model that produces 0.075 solar mass ^{56}Ni (Pinto and Woosley 1988b). Based on the non-detection of gamm-lines during the first two observations of M82 and the first three of NGC 253, and Monte Carlo simulations we can exclude a recurrence time of less than 0.5.yr for a Type Ia (SN rate of 2 yr^{-1}) and 0.15 yr for Type Ib supernova (SN rate of 7 yr^{-1}) models in starburst galaxies.

To further constrain the limit on supernova rates we have added the last VP of NGC 253 and three viewing periods on SN1993J in M81. M81 and M82 are indistiguishable in the OSSE field of view, hence these three VPs can be considered as M82 observations. We further assumed that the supernova rates are the same in all

starbursts. Generating Monte Carlo histories of these 9 viewing periods over a starburst time of 10^6 years we have obtained a 3σ upper limit of 1 SN yr^{-1} for Type Ia (Fig 2).

A set of observations of NGC 253 and M82 are suggested to maximize the chances of gamma-ray line detection from these sources-this will also ensure better sensitivity for detecting diffuse emission. We have tried to maximize the probability using two observation periods where the source is detected at least during one. Fig. 3 shows how the separation between two periods change the probability of detection. For example, the probability of detection for Type 1b model WR6Cfm with a 1 yr recurrence time is ~40% if the separation between the observations is ~20 days . The probability increases reaching a plateau at around ~180 days after which it remains constant.

Fig. 2 Probability of a SN Type Ia line detection as a function of the supernova rate for the 9 viewing periods used in the analysis. The 3σ upper limit to the Type Ia rate is ~1 yr^{-1}.

If the cosmic ray electrons are supplied by supernova explosions, then making use of the minimum energy requirements (to deduce the cosmic ray density) given by Longair (1981) and Miley (1980), and an average supernova energy release, we can estimate the recurrence time of supernovae, t_{SN}, from the following relation:

$$\varepsilon = \frac{t_{elec}}{t_{SN}} \frac{E_{SN}}{V}$$

where telec is the electron lifetime or the characteristic escape time from the confinement volume V, E_{SN} is the average energy release in cosmic rays per SN, and ε is the cosmic ray energy density. V is the infra-red emitting volume used in the diffuse emission estimation for NGC 253 (~2.5 ∞ 10^{64} cm^3). t_{elec} is assumed to be ~ 10^6 yrs. One of the unknowns in this calculation is k, the ratio of proton energy density to that of electron's. For a value of k ~ 100 (which is valid at the top of the atmosphere), the minimum energy in cosmic rays increases by an order of magnitude. In the following calculation, we have taken k to be 1; the energy density increases by a factor of ~ 1.5. In this case E_{SN} is assumed to be 2 ∞ 10^{49} ergs, where the average electron energy yield of a supernova is 10^{49} ergs. Using the observed radio intensities for NGC 253 given in Klien et al. (1983)

we estimate the minimum energy in the starburst nuclei following Miley (1980). Assuming the size of the emitting region to be 2.5' ∞ 0.35' and the path length through the source in the line of sight to be 500 pc, we derive an energy density, ε of 10^{-10} ergs cm^{-3}. Hence, from the equation we get t_{SN} to be 4 yrs. On the other hand, our initial observational t_{SN} of 0.5 yr (for Type Ia) and 0.15 yr (for Type Ib) provide an upper limit to the cosmic ray electron density in starbursts to be $4 \infty 10^{-9}$ ergs cm^{-3}. Further observation can give a proper estimation of t_{SN} and consequently a better understanding of the energy density in starburst environment.

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Fig.3 – Gamma-Ray line (847 keV) detection probability at least in one of the two observations.

Probability

847 keV γ-line prob. detection at least in one of two obs.

3.4 Mpc distance

$T_{SNe\ recurrence} = 1$ year

Days Between Two Observations

W7 $f_{escp} = 1$

W7

WR6Cfm $f_{escp} = 1$

0.075 $M_\odot$ ^{56}Ni $f_{escp} = 1$

WR6Cfm

W10hmm