

OBSERVATION OF THE STARBURST GALAXY NGC 253 WITH THE OSSE INSTRUMENT

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ABSTRACT

Gamma-ray observations of the nearby starburst galaxy NGC 253 over the energy range 0.06–10 MeV have been obtained with the OSSE spectrometer. The source was detected up to 200 keV with a total significance of 4.2σ . When attributed to NGC 253 this corresponds to an estimated luminosity of 3×10^{40} ergs s^{-1} . The spectrum is fit by a power law of photon index ~ 2.5 . A search for $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$ supernova gamma-ray lines yielded no significant detection: the 3σ upper limits at 0.158, 0.847 and 1.238 MeV are 4×10^{-5} , 8×10^{-5} and 9×10^{-5} ph $\text{cm}^{-2} \text{s}^{-1}$, respectively. We find that inverse Compton scattering is insufficient to explain the observed continuum radiation. Bremsstrahlung and discrete sources may account for the flux. We also consider the possibility that the detected emission may result from low energy continuum from scattered gamma-ray lines produced by a very recent Type Ia or Ib supernova outburst in NGC 253.

INTRODUCTION

NGC 253 is the third brightest infrared galaxy with a luminosity of $\sim 4 \times 10^{10} L_{\odot}^1$ in the far infrared band. This nearby (~ 3 Mpc) spiral Sc galaxy is undergoing extensive star formation within its central few kilo-parsecs where it is also very bright in X-rays and radio. The *Einstein* IPC images have revealed a plume of X-ray emission extending above the galactic plane² possibly bearing the evidence of nuclear outflows similar in nature to M82. The outflowing gas is believed to be heated by the energy released during supernova explosions³. The high rate of star formation in the starburst nuclei is biased towards producing massive stars. These stars, being luminous and massive ($3\text{--}100M_{\odot}$), have very short lifespans with most of them resulting in supernovae: massive C/O Wolf-Rayet stars undergo strong mass-loss and explode as Type Ib SN, whereas O and B stars generally evolve into Type II SN⁴. Supernova rates from starburst galaxies have been estimated from radio observations of M82⁵ and NGC 253⁶ and are in the range (0.1–0.3) supernova/yr within the inner 600 pc for those galaxies. However, more recently, Ulvestad and Antonucci suggest this rate may

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be too optimistic⁷. A Type Ia or Ib supernova in the NGC 253 core may produce gamma-ray lines detectable to the OSSE instrument. In this paper, we present the results of the first gamma-ray observation of NGC 253 by the *Compton Gamma-Ray Observatory's (CGRO) Oriented Scintillation Spectrometer Experiment (OSSE)*.

OBSERVATIONS AND RESULTS

a) Observations: The OSSE instrument consists of four actively shielded NaI(Tl)-CsI(Na) phoswich detectors. Each of the detectors has a $3.8^\circ \times 11.4^\circ$ (FWHM) field-of-view. The instrument observes each individual source in the “source–background” method over the energy range 0.06–10 MeV. A detailed description of the instrument can be found in Johnson et al.⁸. NGC 253 was observed with the OSSE in 5 separate viewing periods for a total observation time of $\sim 10^6$ s. The last two observations were carried out with a different scan mode and consequently had little source exposure. The observation schedule of the remaining 3 viewing periods are shown in Table 1 where col. 1 denotes the GRO viewing period (VP) number, col. 2 shows the dates of observation, col. 3 gives exposure times in seconds and col. 4 the total number of detectors used in the observation.

TABLE 1

Viewing Period	Date	Exposure (sec)	Number of Det.
9	9/5/91 16:13 – 9/11/91 23:34	3.31×10^5	4
13.5	11/7/91 18:20 – 11/14/91 17:03	9.76×10^4	4
16	12/14/91 01:40 – 12/28/91 18:06	2.71×10^5	2

NGC 253 is located very near to the galactic south pole ($l = 24^\circ.20$ and $b = -87^\circ.86$). This position was mostly observed as a secondary target whenever the primary target was the Galactic Center. The accumulation schedule for each of the four detectors alternated between source observations and background measurements. The background fields are checked for potential gamma-ray sources using the HEAO A2 all sky map⁹; no bright sources were found. A quadratic background estimation is performed by interpolating between two background observations accumulated before and after the source observation¹⁰. Background subtraction for each detector is carried out and the individual difference spectra for each detector is summed. A count spectrum, obtained by folding model photon spectrum through the instrument response matrices, is compared with the summed data and the model parameters are modified to achieve the best fit.

b) Results: We have used simple power law models to obtain the continuum photon fluxes. The emission spectrum of the full data set is fit by a power law with a photon index of 2.55 ± 0.79 ($\chi^2 = 415.07$, $\text{ndof}=445$). In Table 2, the measured fluxes obtained during different viewing periods are shown. The significance of the detection is 4.2σ . The flux over the 60–200 keV band is 3×10^{-11} ergs cm^{-2} s^{-1} . The derived photon spectrum is shown in Figure 1. At X-ray energies, fluxes measured by Ginga over the energy range 2–10 keV are also given. Ohashi et al.¹¹ find that both thermal bremsstrahlung and power law models give acceptable fits to Ginga results, although they prefer a thermal

spectrum with $kT \sim 6$ keV because the derived N_{H} for power law model is much higher than the Galactic value and contradicts the *Einstein* IPC results. We estimate the Ginga photon fluxes from their power law spectral parameters and show that even a power law extrapolation of Ginga data into the OSSE regime yields fluxes an order of magnitude below the OSSE data points. Expected gamma-ray spectra for a Type Ia and a Type Ib supernova near their peak hard X-ray luminosity (see *Discussion* for details), scaled to the distance of NGC 253, are also shown.

TABLE 2

Energy Bins	VP 9	VP 13.5 + VP 16	Total
	ph cm ⁻² s ⁻¹ MeV ⁻¹	ph cm ⁻² s ⁻¹ MeV ⁻¹	ph cm ⁻² s ⁻¹ MeV ⁻¹
60 – 72 keV	$(3.00 \pm 3.82) \times 10^{-3}$	$(3.44 \pm 3.81) \times 10^{-3}$	$(3.28 \pm 2.75) \times 10^{-3}$
72 – 88 keV	$(2.10 \pm 1.94) \times 10^{-3}$	$(1.95 \pm 1.92) \times 10^{-3}$	$(2.06 \pm 1.39) \times 10^{-3}$
88 – 110 keV	$(0.92 \pm 0.87) \times 10^{-3}$	$(2.60 \pm 0.85) \times 10^{-3}$	$(1.82 \pm 0.62) \times 10^{-3}$
110 – 133 keV	$(0.48 \pm 0.70) \times 10^{-3}$	$(1.02 \pm 0.67) \times 10^{-3}$	$(0.77 \pm 0.49) \times 10^{-3}$
133 – 166 keV	$(0.26 \pm 0.67) \times 10^{-3}$	$(1.11 \pm 0.65) \times 10^{-3}$	$(0.71 \pm 0.47) \times 10^{-3}$

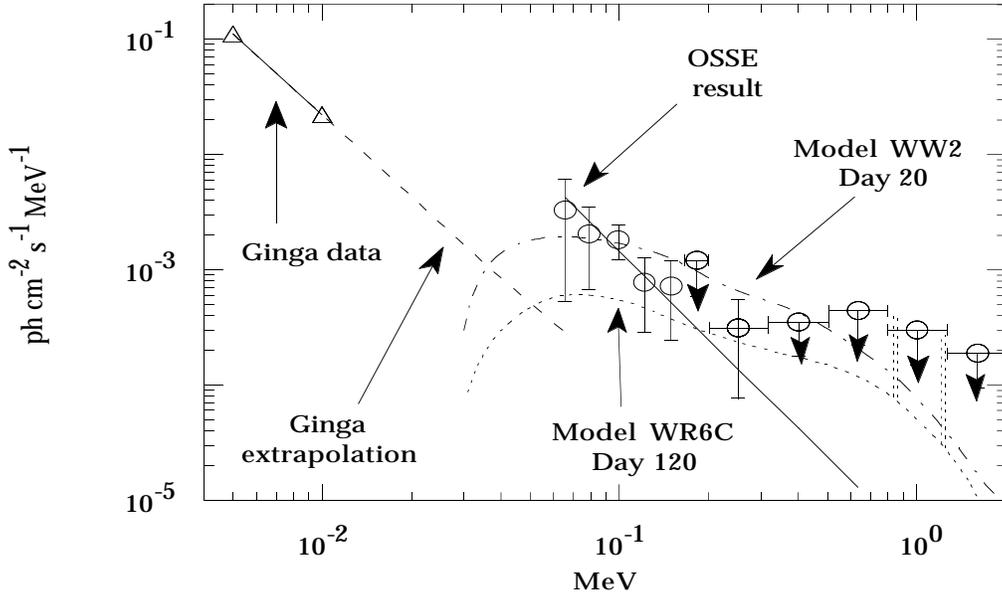


Fig. 1 – The derived photon fluxes for NGC 253. The Ginga X-ray points and their extrapolation to higher energies are also shown. The continuum emissions from a Type Ia (Model WW2) and a Type Ib SN (Model WR6C) are given. The 0.847 and 1.238 MeV lines of WW2 are not shown for clarity.

A line search was carried out at energies corresponding to lines from $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$ decay at 0.158, 0.847 and 1.238 MeV. The line widths are taken as 3.5% of the rest energy following the calculation of Chan and Lingenfelter¹² for a Type Ia supernova. The search failed to show any significant flux. The 3σ upper limits on the flux for the 0.158, 0.847 and 1.238 MeV lines are 4.3×10^{-5} , 8×10^{-5} and 9×10^{-5} photons cm⁻² s⁻¹, respectively.

DISCUSSION

The origin of diffuse hard X-rays or low energy gamma-rays in a starburst galaxy would include inverse Compton effects, electron bremsstrahlung or thermal emission from hot supernova gases. Discrete sources such as X-ray binaries or individual supernova outbursts may also substantially contribute to the emission. The emission from young, massive Population I binary X-ray sources (with $kT > 10$ keV) can be a component of the hard X-ray spectrum, but the number of such sources needed to explain the entire OSSE flux would be in the range of 10^3 – 10^4 .

a) Inverse Compton Emission: The contribution of inverse Compton scattering of relativistic electrons off the far infrared photon field to the total X-ray emission in starburst galaxies has been considered with respect to M82^{13,14}. The number density of the relativistic electrons can be assessed from the radio observations. The emission in the radio range is assumed to be primarily of synchrotron origin and coming from the same set of relativistic electrons responsible for the inverse Compton emission. The FIR photon density can be calculated from the total FIR luminosity and the spatial extent of the FIR emission. Our estimated IC luminosities for NGC 253, in the range 0.06–0.2 MeV, for magnetic field values of 1 and 5 μG , are 6×10^{39} and 4×10^{38} erg s^{-1} , respectively. The observed luminosity over the same energy range is $\sim 3 \times 10^{40}$ ergs s^{-1} . Even given the uncertainties in such calculations, we find that inverse Compton scattering accounts for only a small fraction of the emission seen.

b) Electron bremsstrahlung: At 100 keV, the bremsstrahlung contribution could be at least a factor of 2 higher than inverse Compton scattering in our galaxy¹⁵. Hence, it is not unlikely that the bremsstrahlung contribution could be large in NGC 253, but a proper estimation would require a better understanding of the cosmic ray and nucleon density in NGC 253 core.

c) Supernova continuum: We consider the possibility that the detected continuum emission arises from a Type Ia or Ib SN outburst in NGC 253 but with lines obscured by overlying material. The continuum emission is due to photons in the gamma-ray lines of the radioactive decay chain of ^{56}Ni which are degraded in energy through Compton down-scattering in the expanding envelope. We find that the Monte-Carlo calculations of Burrows and The¹⁶ for a Type Ia SN (model WW2 of Woosley and Weaver¹⁷), when scaled to the distance of NGC 253, predict continuum flux values at 100 keV (at day 20–100) at the same level as the detected flux from NGC 253. However, the peak 847 keV flux for a Type Ia SN (WW2 model) occurs at day ~ 70 and is 3×10^{-4} $\text{ph cm}^{-2} \text{ s}^{-1}$. The absence of this line in the observations makes it unlikely that the continuum emission is due to a Type Ia SN. Similar calculations (Model WR6C of The, Clayton and Burrows¹⁸) carried out for a Type Ib Wolf-Rayet SN (Ensmann and Woosley¹⁹) yield peak continuum flux values (at day 80–150) at factors of 4–5 lower than what have been observed. Given the uncertainties involved in the estimation of the diffuse emission, discrete source contribution, parameters of the SN model and distance to NGC 253, we cannot rule out that a Type Ib explosion could account for much of the observed continuum flux. Furthermore, the peak flux in the 847 keV line for WR6C model ranges from 3.4×10^{-6} to 5×10^{-5} $\text{ph cm}^{-2} \text{ s}^{-1}$

and would not have been detected by the OSSE. The models WW2 and WR6C are used only for illustration purposes; the detailed structure of the spectrum depends on the initial mass, expansion velocity and Compton opacities of the supernova. The marginal variability seen in the 88–166 keV band over a period of 60 days (see Table 2) might be explained by the evolving Compton opacity of the supernova ejecta, although the low significance of the detection makes it difficult to choose a specific model to explain the observation.

A Type Ib event is more likely to occur than a Type Ia in a starburst core. The starburst phenomenon produces more massive stars, including Wolf-Rayet stars, which can undergo strong mass loss and explode as Type Ib SNe. What is the plausibility of Type Ia supernovae in the starburst core? The conventional belief is that the progenitors of Type Ia's are old ($\sim 10^{10}$ yrs) and have low initial mass. But Oemler and Tinsley²⁰, using a sample of 178 supernovae in external galaxies, find that Type Ia SNe occur more frequently in spiral than in elliptical galaxies and the SNe rate is proportional to the current star formation rate. Although these authors do not distinguish between Type Ia and Ib SNe, Filippenko²¹ argues that their sample contains relatively few Type Ib SNe and is representative of Type Ia. In star forming regions, possible evolution of massive stars ($> 8M_{\odot}$) in close binaries into Type Ia SNe, within a short time scale (\sim a few times 10^7 yrs), is not ruled out^{22,23}. But the short timescale will not allow such systems to move very far from their birthplaces (HII regions) before explosion and as Type Ia SNe are not known to occur near HII regions²¹ it would seem to exclude massive stars as progenitors of Type Ia SNe. Whether that is indeed the case, needs further observational verification. In this respect, gamma-ray observations, with the potential to detect supernovae signatures through the dense starburst nuclear regions, serve as a powerful diagnostic tool. The possibility, that we already have detected an extragalactic supernova signature, is extremely intriguing. If, indeed, the observed flux is due to a supernova outburst, future gamma-ray observations may not yield any detectable flux. Without a supernova explosion it is hard to envision rapid spectral or luminosity variability between observations for an otherwise normal galaxy such as NGC 253.

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