A LIMIT ON THE ^{57}Co GAMMA-RAY FLUX FROM SN 1987A

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Received 1992 March 30; accepted 1992 July 21

ABSTRACT

We studied the γ -ray flux from SN 1987A with a balloon-borne detector in Brazil on 1990 November 29. By comparing on- and off-source data, we obtained limits to the total γ -ray flux due to ^{57}Co decays and presumed pulsar activity. If the pulsar contribution is neglected, an upper limit (90% confidence limit) is set to the total ^{57}Co contribution above 60 keV at $2.7 \times 10^{-4} \text{ cm}^{-2} \text{ s}^{-1}$ where the 122 keV line contribution is $1.0 \times 10^{-4} \text{ cm}^{-2} \text{ s}^{-1}$. The corresponding limit on the abundance ratio of ^{57}Co and ^{56}Co is 3.4 times that of the Sun. The present upper limit implies that the reported leveling off in the light curve of SN 1987A is primarily due to the pulsar activity. If the pulsar is Crab-like (photon index -2.2), the light curve requires an energy outflow greater than $0.95 \times 10^{37} \text{ ergs s}^{-1}$ (above 1 keV) now being supplied to SN 1987A by its presumed pulsar.

Subject headings: gamma rays: observations — nuclear reactions, nucleosynthesis, abundances — supernovae: individual (SN 1987A)

1. INTRODUCTION

Since the advent of SN 1987A, theoretical studies of the nucleosyntheses in supernovae and the chemical composition of supernova remnants have been deepened to higher accuracy and greater details (see, e.g., Nomoto et al. 1991a; Chevalier 1992). Observations on SN 1987A in several wavelength regions have allowed us to determine the abundance of some critical nuclides including ^{56}Ni . Analyses of observational data including the early turn-on of the γ -ray and X-ray fluxes have been interpreted as manifestations of the turbulent nature of the supernova explosion.

Among the multitude of nuclides produced in the supernova, the abundance of a few unstable nuclides with long-lived decay chains is of great interest since they are expected to become energy sources as time progresses. These nuclides are ^{56}Co ($\tau \sim 0.3 \text{ yr}$), ^{57}Co ($\tau \sim 1.1 \text{ yr}$), and ^{44}Ti ($\tau \sim 68 \text{ yr}$). Among them ^{56}Co is the dominant energy source in the early life (4 months to 3 yr) of the supernova. In fact the bolometric light curve kept decaying monotonically until recently, in accordance with the lifetime of ^{56}Co (e.g., Nomoto et al. 1991a; Chevalier 1992). From the light curve, the amount of ^{56}Ni (the parent of ^{56}Co) produced in the supernova has been estimated at $0.073 M_{\odot}$ (Nomoto et al. 1991b). Direct measurements of the line γ -ray fluxes due to the decay $^{56}\text{Co} \rightarrow ^{56}\text{Fe}$ ($E = 847 \text{ keV}$, 1238 keV) by the *Solar Maximum Mission* (Matz et al. 1988; Leising & Share 1990) and four balloon experiments (Mahoney et al. 1988; Sandie et al. 1988; Rester et al. 1989; Tueller et al. 1990) gave values consistent with the above estimate of the initial ^{56}Ni abundance. It is, however, the only

nuclide among the three whose abundance has been determined to some accuracy.

Recently, CTIO (Cerro Tololo Inter-American Observatory) and ESO (European Southern Observatory) reported that the UVOIR light curves started to level off since ~ 900 days after the explosion (Bouchet, Danziger, & Lucy 1991; Suntzeff et al. 1991). Such a change has been expected to occur when either ^{57}Co , ^{44}Ti , or the presumed pulsar activity becomes an appreciable energy source.

The theoretically expected abundance of ^{44}Ti falls short of being of any significance at this stage of the supernova's life (e.g., Nomoto et al. 1991a; Woosley & Hoffman 1991). Observations in the mid-IR made by Danziger (1991) suggest that the abundance ratio of ^{57}Co to ^{56}Co cannot be significantly higher than that in the Sun $\langle ^{57}\text{Co}/^{56}\text{Co} \rangle^1 = 1.5$. No X-ray flux has been detected since around day 800 after the explosion (Inoue et al. 1991; Sunyaev et al. 1990). Sunyaev et al. (1990) calculated an upper limit to the pulsar luminosity in the energy band between 1 and 1000 keV: $L_{>1 \text{ keV}} < 4.4 \times 10^{38} \text{ ergs s}^{-1}$ for photon index 2.1 for day 830. This is, however, not inconsistent with the UVOIR light curve measured by CTIO and ESO. Woosley & Hoffman (1991) concluded from a theoretical study of explosive silicon burning that $\langle ^{57}\text{Co}/^{56}\text{Co} \rangle$ is likely to be between 0.5 and 2.5.

The current status calls for direct measurements on the two possible gamma-ray sources. The observation was carried out

¹ $\langle ^{57}\text{Co}/^{56}\text{Co} \rangle$ is the abundance ratio of the $A = 57$ and $A = 56$ isotopes in the $\text{Ni} \rightarrow \text{Co} \rightarrow \text{Fe}$ decay chain normalized to that in the Sun: $\langle ^{57}\text{Co}/^{56}\text{Co} \rangle \equiv [X(^{57}\text{Ni})/X(^{56}\text{Ni})]/[X(^{57}\text{Fe})/X(^{56}\text{Fe})]_{\odot}$.

FIG. 1.—Schematic drawings of one well-type phoswich counter unit (a) and the Welcome 1 detector (b)

on 1990 November 29 (local time, day 1375 after the outburst) in the area around São Paulo, Brazil, for about 160 minutes with our hard X-ray/ γ -ray detector aboard a stratospheric balloon.

2. DETECTOR

The detector system used in the observation consists of 64 “well-type” phoswich counters (Kamae et al. 1992; Murakami et al. 1992) and 36 anticounters (Fig. 1). This detector system will be referred to as Welcome 1.

The well-type phoswich counter is made of a small inorganic scintillator with a fast decay time (the detection part) glued to the interior bottom surface of a well-shaped block of another inorganic scintillator with a slow decay time (the shielding part). The well-shaped shielding part acts as an active collimator as well as an active shield. The whole assembly is viewed by a phototube from the exterior bottom surface of the shielding part (Kamae et al. 1992). By using an appropriate pulse-shape discriminator (PSD), hard X-rays/gamma-rays that have deposited energy only in the detection part can be selected.

The present counter is the first model of the well-type phoswich counter and uses a new scintillator Gd_2SiO_5 doped with Ce(0.5%) (GSO) for the detection part (Takagi & Fukazawa 1983; Ishibashi et al. 1989), and CsI(Tl) for the shielding part. The characteristics of the detector are summarized in Table 1.

Since the well-type phoswich counter integrates the shielding and collimation parts and facilitates finer active collimation, it not only reduces external background but also provides the instrument with a nearly 4π anticounter for the internal β - γ background (Kamae et al. 1992). Its simple shape and reduced count rate allow units to be assembled in a compound-eye configuration (Fig. 1b). Here each unit is surrounded by eight neighbors which can be used as additional

active shields. The observed off-source count rate (after the event selection described below) and the internal background rate (the rate due to radioactivity in GSO crystals) of Welcome 1 are shown in Figure 2 with a Monte Carlo estimation of the external background rate (the rate due to external sources). The measured S/N ratio for the Crab nebula is about 1.2/1.0 in the energy range between 100 and 200 keV: should the atmospheric attenuation ($1/2.5$ at 4 g cm^{-2}) have not existed, the S/N would have reached 3/1.

3. OBSERVATION

Welcome 1 was flown from the Instituto Nacional de Pesquisas Espaciais (INPE) balloon base in Cachoeira Paulista, in the state of São Paulo, Brazil, ($45^\circ 00' 34'' \text{ W}$, $22^\circ 39' 44'' \text{ S}$) on 1990 November 29 (local time, 1375 days after the explosion of SN 1987A). The detector reached ceiling altitude of 37.7 km (4 g cm^{-2}). The observation of SN 1987A started at 1:00 A.M., 1990 November 30 (local time). On-source and off-source observations were alternated at an interval of ~ 20 minutes. In total we observed SN 1987A (on-source) for about 85 minutes and background (off-source) for about 75 minutes. During the observation, the detector was set at a fixed elevation angle (43°), and its azimuth angle was adjusted to follow the direction of SN 1987A approximately every 10 minutes. During the

FIG. 2.—Observed off-source spectrum (histogram), the measured internal background (filled circles), and the Monte Carlo simulated external background (solid line). Broad peaks at around 368 and 511 keV are due to ^{152}Gd α -decays (2.14 MeV) in GSO and to e^+ annihilations, respectively.

TABLE 1
CHARACTERISTICS OF WELCOME-1

Characteristic	Value
Energy range	60–800 keV
Energy resolution (FWHM)	28% at 122 keV, 12% at 511 keV
Geometrical area	740 cm^2
Full peak efficiency	98 at 122 keV, 30% at 511 keV
Background rate	$1.5 \times 10^{-4} \text{ cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$ at 122 keV
Pointing	Elevation: fixed Azimuth: $\sim \pm 1^\circ$
Aperture (HWHM)	7.7 at 122 keV; 9.1 at 511 keV

background run, the detector was pointed 20° – 30° away to the east or west of SN 1987A.

Pointing was done by using a geomagnetic sensor. The direction of the detector was monitored by a star camera to about $\pm 0.02^\circ$. During the observation, all counters but one operated normally.

4. DATA ANALYSIS

In data analysis we rejected events within 1.5 ms of large-energy-depositing events (≥ 50 MeV, mostly charged particles) in the same counter or in a neighboring counter. This effectively eliminated unwanted baseline fluctuation after the incidence of high-energy charged particles. We then rejected events with one or more hits in the neighboring counters to eliminate Compton-scattered γ -rays.

As the result of the above event selection, the total on-source and off-source live times were reduced to 3397 and 2997 s for 63 counters (efficiency of about 66.6%). The spectrum after the event selection was well reproduced by the measured internal background due to radioactive contamination in the detection part (GSO) and simulated atmospheric and celestial diffuse background with the energy dependence given by Gehrels (1985).

The overall gain and the live time were calibrated for every counter by using the broad peak at around 368 keV (Fig. 2) due to α -decays of ^{152}Gd in GSO ($E_\alpha = 2.14$ MeV, rate = 0.167 Hz/counter). To follow the time variation at fine steps and yet to keep high statistical accuracy, the ^{152}Gd α -decays were integrated for 90 minutes centered around time bins set at 5 minute steps. This procedure eliminated over-compensation of statistical fluctuations by gain adjustment. The resultant time variation of the overall gain is consistent with what is expected from the temperature variation recorded during the observation.

The four sets of on- and off-source spectra were then normalized according to the effective live time and the effective area, and then four on-off subtractions are made: the results do not show any significant deviation from zero when integrated over the detector energy resolution. The electronically measured effective live times for on and off observation were in accord with those estimated from the total numbers of the ^{152}Gd α -decays counted. Finally the four on-off spectra were

FIG. 3.—Observed γ -ray spectrum from the direction of SN 1987A: (a) Difference between the on-source and the off-source spectra (effective time 3397 s, effective area 592 cm^2); (b) Statistical significance of data points. The crosses and the filled circles are the 90% and 95% CL upper limits, respectively.

summed to give the histogram shown in Figure 3a. The statistical significance of data points are shown in Figure 3b. When folded with the energy resolution, we do not see any deviation greater than 1.3σ up to 400 keV.

The nonobservance of any line feature in our data has led us to set upper limits on the ^{57}Co γ -ray flux and the pulsar energy outflow from SN 1987A. We assume here that there are two γ -ray sources of a fixed flux amount, ^{56}Co of $0.073 M_\odot$ as determined from the early light curve, and ^{44}Ti of $9.2 \times 10^{-5} M_\odot$ (Nomoto et al. 1991b), and two γ -ray sources of an unknown amount ^{57}Co , and pulsar activity:

$$f_{\text{obs}}(E_\gamma) = f_{56}(E_\gamma) + f_{44}(E_\gamma) + N_1 f_{57}(E_\gamma) + N_2 f_{\text{pulsar}}(E_\gamma), \quad (1)$$

where

$f_{\text{obs}}(E_\gamma)$: Observed γ -ray flux ,

$f_{56}(E_\gamma)$: ^{56}Co γ -ray flux for $^{56}\text{Co} = 0.073 M_\odot$,

$f_{44}(E_\gamma)$: ^{44}Ti γ -ray flux for $^{44}\text{Ti} = 9.2 \times 10^{-5} M_\odot$,

$f_{57}(E_\gamma)$: ^{57}Co γ -ray flux for $\langle ^{57}\text{Co}/^{56}\text{Co} \rangle = 1$,

$f_{\text{pulsar}}(E_\gamma)$: pulsar γ -ray flux for the energy outflow $10^{38} \text{ ergs s}^{-1}$ (photon index = -2.2 assumed) ,
 E_γ : γ -ray energy ,

N_1, N_2 : Normalization factors .

The functions f_{56} , f_{44} , f_{57} , and f_{pulsar} are numerically supplied by S. Kumagai (1992, private communication; the same functions have been used in Kumagai et al. 1989, and we take the distance to SN 1987A to be 55 kpc) at the abundances or intensity listed above. These numerical functions were calculated using Model 14E1 of Shigeyama & Nomoto (1990).

Chi-square is calculated for the data shown in Figure 3a by assuming the form given in equation (1) for various normalization factors. The sets of points (N_1, N_2) where the confidence level (CL) reaches 68.3%, 90%, or 95% form three lines shown in Figure 4. The two superposed curves in Figure 3a correspond to the 90% CL upper limit ($N_1 = 3.4, N_2 = 0$) and the 95% CL upper limits ($N_1 = 4.8, N_2 = 0$). The 90% CL upper limit ($N_1 = 3.4, N_2 = 0$) corresponds to the ^{57}Co 122 keV line flux of $1.0 \times 10^{-4} \text{ cm}^{-2} \text{ s}^{-1}$. The 90% CL upper limit ($N_1 = 0, N_2 = 2.3$), on the other hand, corresponds to a Crab-like pulsar with energy outflow of $L_{>1 \text{ keV}} = 2.3 \times 10^{38} \text{ ergs s}^{-1}$ or about 2.3 times the energy emitted by the Crab nebula.

FIG. 4.—Upper limits at 68.3%, 90.0%, and 95.4% CL for the ^{57}Co abundance and the pulsar energy outflow.

5. CONCLUSIONS

Several theoretical analyses have already been made on the measured light curve (Kumagai et al. 1991 and Suntzeff et al. 1991). According to Kumagai et al. (1991), $\langle {}^{57}\text{Co}/{}^{56}\text{Co} \rangle$ needs to be greater than 20 to reproduce the ESO light curve if the energy is supplied only by the ${}^{57}\text{Co}$ decay. They determined that $\langle {}^{57}\text{Co}/{}^{56}\text{Co} \rangle$ between 5 and 10 is required if the CTIO light curve is to be reproduced by the ${}^{57}\text{Co}$ decay. Suntzeff et al. (1991) fitted the CTIO data up to day 1600 and concluded that $\langle {}^{57}\text{Co}/{}^{56}\text{Co} \rangle$ is 5 ± 1 .

In the present study, an upper limit (90% CL) is set to the total ${}^{57}\text{Co}$ γ -ray flux above 60 keV at $2.7 \times 10^{-4} \text{ cm}^{-2} \text{ s}^{-1}$ where the 122 keV line contribution is $1.0 \times 10^{-4} \text{ cm}^{-2} \text{ s}^{-1}$. The corresponding limit on the $\langle {}^{57}\text{Co}/{}^{56}\text{Co} \rangle$ is 3.4 and somewhat inconsistent with $\langle {}^{57}\text{Co}/{}^{56}\text{Co} \rangle = 5 \pm 1$ obtained by Suntzeff et al. (1991). Our limit implies, instead, that the major energy source of the present SN 1987A is not ${}^{57}\text{Co}$ decays but probably pulsar activity. If the ESO data around 950–1350 days are combined with the present upper limit, the energy flow out of the presumed Crab-like pulsar is calculated at $L_{>1 \text{ keV}} \sim (0.91, 0.87, \text{ or } 0.80) \times 10^{38} \text{ ergs s}^{-1}$ in addition to

that supplied by ${}^{56,57}\text{Co}$ decays with $\langle {}^{57}\text{Co}/{}^{56}\text{Co} \rangle$ of 1.0, 1.7, or 3.4, respectively. If the CTIO light curve around day 900–1450 is taken, the energy flow of the presumed pulsar is $L_{>1 \text{ keV}} \sim (1.50, 1.35, \text{ or } 0.95) \times 10^{37} \text{ ergs s}^{-1}$ in addition to that supplied by ${}^{56,57}\text{Co}$ decays with $\langle {}^{57}\text{Co}/{}^{56}\text{Co} \rangle$ of 1.0, 1.7, and 3.4, respectively.

This work has been carried out under support of Grant-in-Aid by Ministry of Education, Culture and Science (Monbusho) of Japan. The authors wish to thank Professors J. Nishimura, M. Oda, K. Kikuchi, Y. Tanaka, F. Makino, N. Yajima, K. Sato, and K. Nomoto on the Japanese side, and the INPE directorate and the Government of Brazil on the Brazilian side for advice and assistance that made this Brazilian-Japanese collaboration a success. Special thanks are due to V. W. J. H. Kirchhoff who supervised the project in Brazil and to the INPE and ISAS balloon groups who cooperated in the successful launch. We owe Professor K. Nomoto and S. Kumagai thanks for the theoretical γ -ray spectra used in the fitting.

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