THE ASTROPHYSICAL JOURNAL, 362:235–240, 1990 October 10

A LIMIT ON THE PRODUCTION OF ^{56}Ni IN A TYPE I SUPERNOVA

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Received 1990 March 2; accepted 1990 April 3

ABSTRACT

We have searched the data from the Gamma-Ray Spectrometer on the *Solar Maximum Mission* satellite for evidence of gamma-ray line emission from the decay of ^{56}Co in the Type Ia SN 1986G. We found no significant flux at either 847 or 1238 keV, the energies of the two strongest decay lines. Based on the data, we can set a 3 σ upper limit of 0.4 $M_{\odot}$(D/3 Mpc)^2 on the amount of ^{56}Ni produced in the explosion. This value is consistent with radioactive models of Type I light curves. For distances less than 3 Mpc the limit is inconsistent with most models of SN Ia as thermonuclear explosions of white dwarfs.

Subject headings: gamma rays: general — nucleosynthesis — stars: supernovae

I. INTRODUCTION

Type Ia supernovae (SN Ia) are thought to result from the thermonuclear explosion of white dwarfs which have reached critical mass by accreting material from a stellar companion. There are a number of possible evolutionary scenarios which could lead to such an explosion (see, e.g., Iben and Tutukov 1984). The rapid nuclear burning during the explosion produces radioactive elements; in particular, nucleosynthesis calculations have long predicted the formation of a significant amount of ^{56}Ni in supernova explosions (Truran, Arnett, and Cameron 1967; Bodansky, Clayton, and Fowler 1968). Recent estimates of the amount of ^{56}Ni produced by Type Ia supernovae vary from 0.4 up to 1.4 $M_{\odot}$ (Nomoto, Thielemann, and Yokoi 1984; Sutherland and Wheeler 1984; Woosley, Taam, and Weaver 1986).

The amount of ^{56}Ni formed depends on the details of the explosion. One critical parameter is the speed of the nuclear burning front. Supersonic burning (detonation) converts essentially the entire star to ^{56}Ni and ejects only traces of lighter elements. Subsonic burning (deflagration) produces less energy, less ^{56}Ni, and leaves more lighter elements. There is some spectroscopic evidence for the formation of iron group elements in SN I explosions (Branch *et al.* 1983; Graham *et al.* 1986); optical spectra indicate, however, that not all the stellar material is burned to ^{56}Ni (Branch *et al.* 1982). This argues against detonation models. Studies of deflagration explosions of CO white dwarfs (Nomoto, Thielemann, and Yokoi 1984) give good agreement with observed optical spectra and light curves (Branch *et al.* 1985; Sutherland and Wheeler 1984). For these reasons deflagration models are currently preferred.

The ^{56}Ni produced in the explosion decays ($\tau_{1/2} = 6.1$ days) to ^{56}Co, which in turn decays ($\tau_{1/2} = 77.1$ days) to stable ^{56}Fe. Most of the decay energy of ^{56}Ni and ^{56}Co is in the form of gamma rays; at early times, when the overlying material is thick, the gamma rays are trapped and deposit their energy in the envelope. This trapped radiation is thought to provide the energy for the peak of the optical light curve (Colgate and McKee 1969; Colgate, Petschek, and Kriese 1980; Arnett 1979). As the ejecta expand and thin, more of the gamma rays escape unscattered. This decreases the amount of energy available to power the optical light curve and allows some of the gamma rays to escape unscattered. At this point the gamma-ray lines can be detected directly (Clayton, Colgate, and Fishman 1969). Eventually (about day 100), the ejecta become thin enough that almost all the gamma rays escape. The exponential tail of the light curve is then powered by the kinetic energy of the decay positrons (Arnett 1979).

Detailed calculations have been made of the emergence of gamma-ray lines from supernovae (e.g., Gehrels, Leventhal, and MacCallum 1987; hereafter GLM). The strongest gamma-ray lines from ^{56}Co decay are at 847 keV (branching ratio = 100%) and 1238 keV (67.9%). Observation of these gamma-ray lines from a Type I supernova would verify directly that ^{56}Ni was synthesized in such explosions. A gamma-ray measurement of the amount of ^{56}Ni synthesized would tell something about the nature of the explosion, confirm the radioactive model of SN I light curves, and bear directly on the question of whether SN I are in fact standard candles.

We report here on a search for ^{56}Co gamma-ray lines from the recent Type Ia supernova SN 1986G using data from the Gamma-Ray Spectrometer on the *Solar Maximum Mission* satellite. In § II we discuss the optical and infrared observations of this supernova; we use these observations to derive some quantities relevant to the gamma-ray analysis. In § III we calculate the amount of ^{56}Ni expected in SN 1986G, based on the radioactive model of SN I light curves. Section IV describes the process used to accumulate gamma-ray spectra of the supernova, § V covers the modeling of the expected gamma-ray signal, and § VI presents the limits derived by fitting the model to the data. In § VII we compare those limits with the predictions of various models of SN Ia explosions and light curves.

II. SN 1986G IN CENTAURUS A

SN 1986G in the active galaxy Cen A (NGC 5128) was discovered by Evans (1986*a*) on 1986 May 3.5. Highly obscured by the dust lane of Cen A, it reached a maximum blue magnitude of 12.45 ± 0.05 on about May 11 (Phillips *et al.* 1987). The supernova is relatively nearby ($D \sim 3$ Mpc; see below) and shows a very rapid postpeak optical decline.

The optical spectra of SN 1986G lack hydrogen lines, making this supernova Type I by definition; further, the presence of the Si II line at maximum light mark it as Type Ia. However, there are some peculiarities which distinguish this supernova from typical SN Ia. First, the quantity β, defined by Pskovskii (1977) as the rate of decline (in magnitudes per 100

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days) of the blue light curve from maximum to the exponential tail, was equal to 12 for SN 1986G (Phillips *et al.* 1987). In Pskovskii's (1984) sample of 54 Type I supernovae only five had $\beta \geq 12$. Second, there is evidence that this event was underluminous compared to other SN Ia's (Phillips *et al.* 1987). This is consistent with the apparent correlation (Pskovskii 1977, 1984; Branch 1981) between β and maximum blue luminosity. Third, the IR light curve was inconsistent with previously measured light curves of SN Ia and Ib (Frogel *et al.* 1987). Finally, the spectrum near maximum light resembled the spectra of normal SN Ia about 2 weeks after maximum (Meurer 1986). This is reminiscent of SN Ib, where the difference in apparent age is 1 to 2 months (Wheeler and Levreault 1985).

These unusual characteristics may indicate that SN 1986G is a typical SN Ia with some physical parameter(s) of the progenitor system at extreme values, or that it is an unusual type of explosion, or even that it represents an intermediate case between Type Ia and Ib (if such can exist). At any rate, it is advisable to be cautious about generalizing from this event to all SN Ia's.

We discuss below a number of other observational issues related to the interpretation of the gamma-ray limits.

a) Distance to Centaurus A

The distance to Cen A is highly uncertain, with published values ranging over more than a factor of 4. The distance is usually quoted as 5 Mpc, based on Burbidge and Burbidge (1959). However, most recent estimates have fallen in the range 2.0–3.7 Mpc (Davies *et al.* 1984; de Vaucouleurs 1979; Hesser *et al.* 1984; Wilkinson *et al.* 1986). In addition, Sandage and Tammann (1981) give a corrected recession velocity for Cen A with respect to the centroid of the Local Group of 251 km s^{-1}. For Hubble constant $H_0 = 50$–100 km s^{-1} Mpc^{-1}, this implies a distance of $\sim$2.5–5 Mpc. Based on observations of SN 1986G, Phillips *et al.* (1987) estimated its distance to be 3.3 ± 0.6 Mpc (but see § II*c*). A similar result was obtained by Frogel *et al.* (1987) by comparing IR observations of SN 1986G with SN 1971I and 1972E. Based on these results we have adopted a distance of 3 Mpc in quoting mass limits in this paper, but we have explicitly included the dependence on distance in the values.

b) Time of Explosion

In order to relate gamma-ray fluxes from decaying ^{56}Co to the mass of ^{56}Ni produced in the explosion, the actual time of the explosion (t_0) must be estimated. The supernova was first detected by Evans (1986*a*) at mag 12.5 on 1986 May 3.5. Therefore, $t_{max} - t_0 > 7.5$. Evans also placed limits on the SN magnitude of 16 and 15.5 on April 15.55 and April 24.55, respectively (Evans 1986*b*). These limits fall at $t_{max} - t_0 = 25.5$ and 16.5 days.

Based on an extrapolation of the composite light curve of Barbon, Ciatti, and Rosino (1973) for "fast" SN I, the time from explosion to B_{max} appears to be roughly 15 days. This is consistent with a number of theoretical calculations (Woosley and Weaver 1986; Arnett 1982, Graham 1987*a*). It is a bit less than the 21 ± 2 days estimated by Pskovskii for SN I with $\beta = 12$. We adopt a value of $t_{max} - t_0 = 16$ days as consistent with both theory and observation, with a possible uncertainty of about 8 days. Phillips *et al.* (1987) give the time of B_{max} as May 11 ± 1, so the estimated data of the explosion is April 25.

c) Extinction

Phillips *et al.* (1987) derive $E(B-V) = 0.90 \pm 0.10$ from their optical data. This is consistent with the number derived by Rich (1986) of 0.88 ± 0.10. Phillips *et al.* (1987) also find a value for the total *B*-band extinction of 3.6 ± 0.4, assuming $A_B/E(B-V) = 4$. As they mention, this assumption may not be true in the Cen A dust lane. A value of $R = A_V/E(B-V)$ for the dust in the line of sight to SN 1986G was determined by Hough *et al.* (1987) using optical and infrared polarization measurements of the supernova. The wavelength of maximum polarization is directly related to R by $R = (5.6 \pm 0.3)\lambda_{max}$ (Whittet and van Breda 1978). From their measured value $\lambda_{max} = 0.43 \pm 0.01$ μm, Hough *et al.* (1987) conclude that $R = 2.4 \pm 0.13$. The $A_B = 2.2 \pm 0.3$ and $A_B = A_V + E(B-V) = 3.1 \pm 0.3$. This implies a corrected maximum *B*-band magnitude of 9.4 ± 0.3. Note that using this adjusted extinction and following the reasoning of Phillips *et al.* (1987) in comparing SN 1986G to SN 1971I, a distance of 4.0 Mpc, not 3.3 Mpc, would be found.

III. SN 1986G AND RADIOACTIVE MODELS OF SN Ia LIGHT CURVES

We can calculate the amount of ^{56}Ni production which would be predicted for SN 1986G by radioactive models of Type I light curves. According to these theories, the bolometric luminosity and the input radioactive decay energy are equal at the time of peak bolometric luminosity (Arnett, Branch, and Wheeler 1985; Sutherland and Wheeler 1984). The input radioactive decay energy at time t after the explosion is

$$L = M_{56} \times [1.4 \times 10^{43} e^{(-t/111.26d)} + 6.3 \times 10^{43} e^{(-t/8.8d)}] \text{ ergs s}^{-1} , \quad (1)$$

where M_{56} is the mass (in units of $M_\odot$) of ^{56}Ni produced in the explosion. Expressed as apparent bolometric luminosity at distance D, the luminosity is

$$L = (2.7 \times 10^{46}) \times 10^{-2m_b/5} (D/3 \text{ Mpc})^2 \text{ ergs s}^{-1} \quad (2)$$

(using Lang 1980, eq. [5-239]). Equating the two expressions gives (cf. Arnett, Branch, and Wheeler 1985)

$$M_{56} = (2.7 \times 10^3) \times 10^{-2m_b/5} (D/3 \text{ Mpc})^2 \times [1.4 e^{(-t/111.26d)} + 6.3 e^{(-t/8.8d)}]^{-1} . \quad (3)$$

In order to estimate the peak bolometric luminosity of SN 1986G, we have constructed approximate bolometric light curves using the data from Table 1 of Phillips *et al.* (1987), combined with bolometric corrections from Schurmann (1983). Temperatures were derived using equation (10) of Arp (1961) and the $B-V$ colors of Phillips *et al.* (1987), corrected for extinction. The peak bolometric magnitudes found by applying this calculation to the *B*- and *V*-band data are 9.12 and 8.96, respectively. Averaging these values yields $m_b \approx 9.0 \pm 0.3$, where the error has been estimated from the error on the extinction and the range of bolometric magnitudes derived from the two wavelength bands. With $D = 3$ Mpc, this implies a peak absolute bolometric magnitude of ~ -18.4

Using this peak apparent bolometric luminosity and a time from explosion to peak of 16 days in equation (3) gives $M_{56} \approx (0.30 \pm 0.16) \times (D/3 \text{ Mpc})^2$ (including the uncertainty in the time of the explosion). This estimate scales with distance in the same way as the gamma-ray limit derived below (§ VI), and so can be directly compared with it.

IV. GAMMA-RAY ANALYSIS

The Gamma-Ray Spectrometer (GRS) has been described in detail elsewhere (Forrest *et al.* 1980). Briefly, the GRS consisted of seven 3″ × 3″ NaI detectors, actively shielded by CsI on the sides and back. The GRS operated in low-Earth orbit from 1980 February to 1989 November. Over that period there was no evidence for long-term gain changes or degradation in resolution.

The spectrometer was usually pointed at the Sun; therefore, SN 1986G transited its field of view, with peak sensitivity occurring in November when Cen A was about 30° from the center of the aperture. Figure 1 illustrates the GRS angular response at 847 and 1238 keV, derived from a Monte Carlo calculation.

The GRS accumulated a 476 channel spectrum covering the energy range ~0.3–8.5 MeV every 16.384 s. These spectra have been summed up to 1 minute resolution, and bad data have been removed. In addition, we do not use data accumulated within ~2.5 hr after passage through the South Atlantic Anomaly to minimize contributions from short-term activation in the spacecraft and instrument. For each orbit, every good 1 minute spectrum is classified as source or background, depending on whether the supernova is visible to the instrument or is occulted by the Earth. One source and one background spectrum are produced for each orbit by summing the two categories of 1 minute spectra. A net source spectrum is calculated by taking a normalized difference of the source and background spectra. To minimize systematics, source minus background differences are calculated for each orbit, and only orbits containing a sufficient amount of background (occulted) data (live time ≥25% of the unocculted live time) are accumulated in the long-term sums. Due to the position of the source and the characteristics of the *SMM* orbit, there are periods when there is little or no occultation of the supernova during an orbit. Because there are insufficient background observations at these times, there are periodic gaps in the supernova measurements.

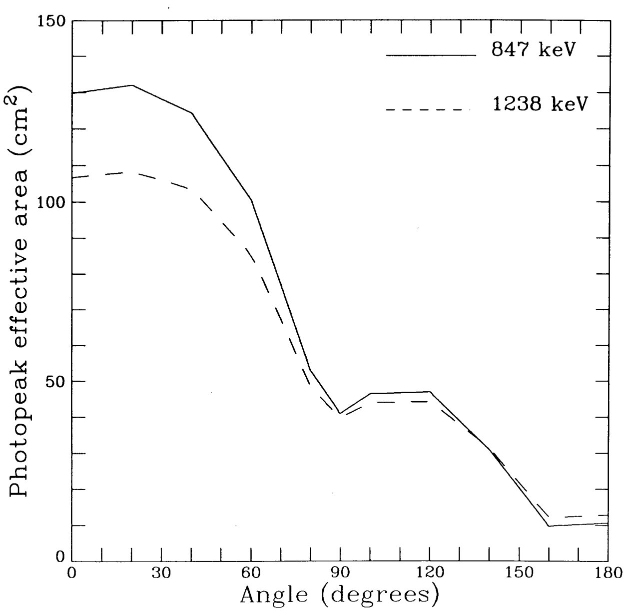

FIG. 1.—The photopeak effective area of the GRS as a function of the angle from the forward direction, at the energies of the two principal gamma-ray lines from the decay of ^{56}Co.

The selected orbital background-subtracted spectra are summed over one satellite orbital precession period (~53 days). These summed spectra are fitted to determine the intensities of the lines of interest. While the orbital subtraction removes most of the background from slowly varying local sources, background sources which change substantially during an orbit (including the atmospheric continuum) may leave residual fluxes in the difference spectra. In order to model these residuals, the fit to the background-subtracted counting rate spectra includes, in addition to the two ^{56}Co decay lines, a power-law continuum and four lines corresponding to observed background features. Two of the background lines (at 1.173 and 1.333 MeV) are from the internal ^{60}Co calibration source, one (at 1.368 MeV) is from ^{24}Na produced in the spacecraft, and one (at ~1 MeV) is of unknown origin. The energies and widths of all six lines are fixed. These are thus eight parameters in the fit, which is made over 66 channels (from 0.75 to 1.48 MeV), giving 58 degrees of freedom for each spectrum.

This technique is essentially the same used for detection of ^{56}Co decay gamma-ray lines from SN 1987A in data from this instrument (Matz *et al.* 1988; Matz, Share, and Chupp 1988). Detection of SN 1987A shows that this method is sensitive to these lines from cosmic point sources. We are, in fact, using the same data, but we have rebinned the spectra into source and background according to the occultation of a source at the position of SN 1986G, instead of at that of SN 1987A. In this rebinning, exposure to the SN 1987A location is equal in the source and background spectra to a level of about 1%; therefore, there will be no significant contribution from a source at the SN 1987A location in the difference spectra for SN 1986G. Moreover, SN 1987A occurred after the first transit of SN 1986G in 1986 November. Note that the measurements of SN 1986G are more sensitive since it is, at least part of the time, in the GRS field of view, while SN 1987A is approximately 90° from the forward direction.

In the fits, the peak positions of the ^{56}Co gamma-ray lines were fixed at their laboratory values. While early emission will be blueshifted, by the time a significant signal is expected in the GRS the line peaks should be at 847 and 1238 keV (GLM). The widths of the two ^{56}Co lines were also fixed in the fits. Based on our calculations and those of GLM, we chose a width corresponding to an intrinsic 847 keV line width of ~40 keV (FWHM). This corresponds to the width of their model 3 (same as Woosley, Taam, and Weaver 1986; model 3) with an average velocity of 11,000 km s^{-1}. The maximum observed velocity in SN 1986G was less than 12,000 km s^{-1} (Phillips *et al.* 1987). Broader assumed line widths will give less sensitive limits.

Figures 2 and 3 show time histories of the fitted intensities of the two ^{56}Co lines. The variations in intensity in both are consistent, by χ^3, with random fluctuations about the fitted means.

V. MODELING THE SUPERNOVA SIGNAL

The fits described above produce time histories of the intensities of the gamma-ray lines. It is then necessary to model the expected time-dependent signal from the supernova and compare this with the measurements to derive a value for the mass of ^{56}Ni produced in the explosion. The components which contribute to the time dependence of the signal are (1) the position of source with respect to center of GRS field of view (and the GRS angular response), (2) the decay of the ^{56}Ni and ^{56}Co, and (3) the transparency of the supernova ejecta

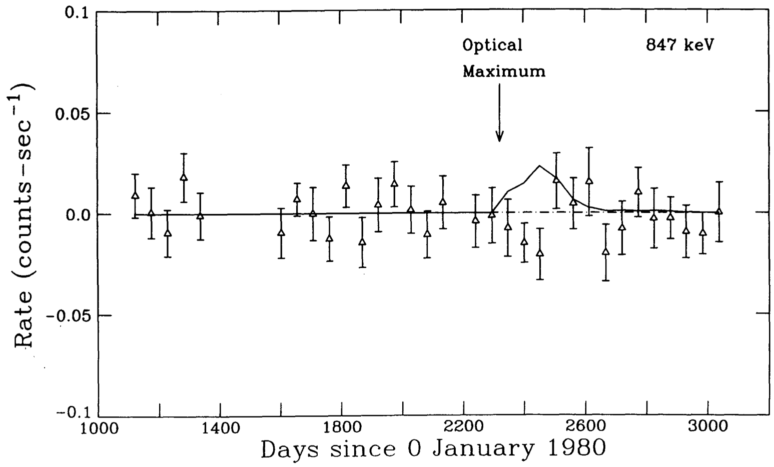

FIG. 2.—The intensities of the 847 keV line fitted to the ~53 day background-subtracted spectra for the supernova position. The data gap between roughly day 1350 and day 1600 is due to missing data in the period before the satellite was repaired in 1984 April. Plotted over the data is the expected response from the 3 σ upper-limit mass at 3 Mpc. The optical maximum occurred on 1986 May 11 ± 1, which is day 2323 in the plotted units.

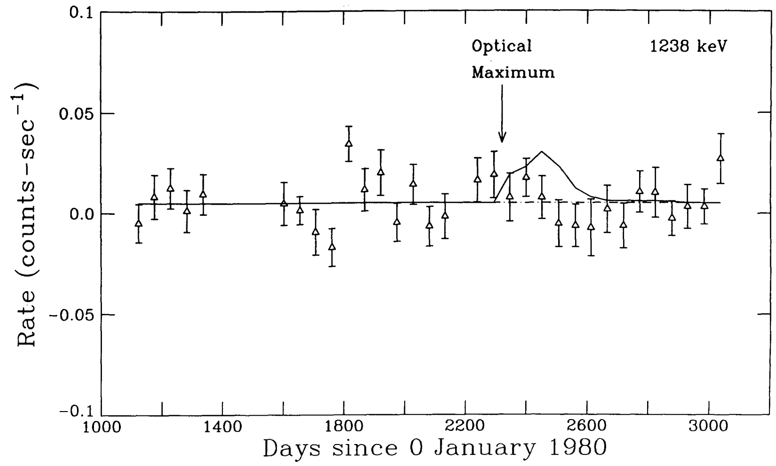

FIG. 3.—As in Fig. 2, except that the 1238 keV line intensities and upper-limit model are shown.

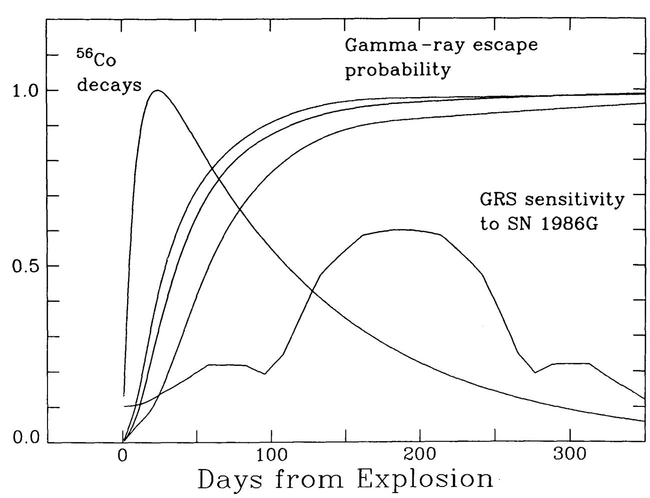

FIG. 4.—The components which contribute to the time-dependent response of the GRS to SN 1986G. The three lines for the gamma-ray escape probability of an 847 keV photon represent the minimum and maximum transmission cases, and well as the transmission corresponding to Woosley, Taam, and Weaver (1986), model 3 (Gehrels 1988, private communication). The number of ^{56}Co decays per second has been normalized to 1 at the maximum. The GRS sensitivity (arbitrarily normalized) to 847 keV photons from the supernova is a function of the angle between the GRS look direction and the source position.

overlying the ^{56}Co. Figure 4 illustrates the time dependence of these components for the 847 keV line from the supernova explosion. The product of these gives the expected signal in the GRS.

In this calculation we have used a revised instrument angular response from a new Monte Carlo calculation. The calculated photopeak effective areas at 847 and 1238 keV are shown in Figure 1. This response is significantly broader than the estimated response used in our original work (Matz *et al.* 1987), implying a higher sensitivity to the supernova off-axis. This gives an improved mass limit. The decay rates of ^{56}Ni and ^{56}Co are based on the standard measurements (Wells, Blatt, and Myerhof 1963; Lagoutine, Legrand, and Bac 1978; both as referenced in Huo *et al.* 1987).

For the gamma-ray transparency of the ejecta at 847 keV we have relied on the calculations of Gehrels, Leventhal, and MacCallum (GLM; and Gehrels 1988, private communication) for Type I supernovae. To cover the likely range of transparencies we have constructed minimum and maximum transmission models from the envelope of all the models shown in Figure 1 of GLM. We have also compared our data to an intermediate case from this paper, their model 3

TABLE 1

SMM/GRS VALUES FOR $M_{56}/M_{\odot}$ AT $D = 3$ Mpc

TRANSMISSION MODEL	LINE(S) FITTED			3 σ Limit
	847 keV	1238 keV	847 + 1238	
Min transmission	-0.20 ± 0.16	0.05 ± 0.23	-0.14 ± 0.14	0.41
Max transmission	-0.19 ± 0.14	0.06 ± 0.20	-0.08 ± 0.12	0.36
WTW, model 3	-0.19 ± 0.14	0.06 ± 0.21	-0.12 ± 0.13	0.38

(corresponding to Woosley, Taam, and Weaver 1986; model 3), with ejected mass equal to 1.0 $M_{\odot}$ and $v_{max} = 20{,}588$ km s^{-1}.

To produce the expected flux at 1238 keV from the GLM calculations we first estimated the average optical depth for 847 keV photons from the given transmission curves, then used a 1238 keV attenuation coefficient of 0.054 cm^2 g^{-1} to get the 1238 keV transmission. Combining this with the instrument sensitivity to 1238 keV photons as a function of time and the known radioactive decay gives the expected time-dependent signal at 1238 keV.

VI. RESULTS

The model time histories derived above are fitted to the measured line intensities shown in Figures 2 and 3 by minimizing χ^2 in a two-parameter fit (mass of ^{56}Ni produced plus a constant). Three limits have been determined for each supernova model: independent limits for each of the two lines, using the appropriate time history model for each line energy, and a limit determined from spectral fits in which the ratio of the 847 and 1238 keV line intensities was fixed at each time according to a model which includes transmission through the supernova ejecta and the angular response of the instrument. For times before the explosion we have set the line ratio in the spectral fits equal to the average value during the 1986 source transit of the instrument field of view. The results are not sensitive to this choice.

The results for the three supernova models, for the individual and combined line fits, are given in Table 1. Best-fit values are shown in each case along with the best 3 σ upper limits, which are based on the combined 847 and 1238 keV line fit. Since the corresponding best-fit mass values are about 1 σ less than zero, we have (conservatively) quoted upper limits which are 3 σ above zero. These upper limit models are plotted along with the data in Figures 2 and 3. None of the data show a significant signal from ^{56}Co decay, and the variations from model to model do not significantly affect the fitted values. The 3 σ upper limit for the minimum transmission case is ~ 0.4 $M_{\odot}(D/3\ \mathrm{Mpc})^2$ of ^{56}Ni produced in the explosion. This corresponds to an average gamma-ray flux of $\sim 2.2 \times 10^{-4} \gamma$ cm^{-2} s^{-1} during the spectral accumulation interval (1986 August 25–October 9) when the signal from the supernova is expected to peak in the GRS.

VII. DISCUSSION AND CONCLUSIONS

The fits to the GRS data show no evidence of any ^{56}Co gamma-ray line emission from SN 1986G. We therefore cannot confirm that ^{56}Ni was formed in the explosion. Our observations do allow the presence of a small amount of ^{56}Co, placing a conservative 3 σ upper limit of 0.4 $M_{\odot}(D/3\ \mathrm{Mpc})^2$ on the amount of ^{56}Ni produced in the explosion. This limit is not sensitive to the specific transmission model assumed.

The mass limit inferred from the gamma rays is consistent at about the 2 σ level with the amount of ^{56}Ni expected based on radioactive models of SN Ia light curves, which for this event predict approximately 0.3 $M_{\odot}(D/3\ \mathrm{Mpc})^2$ (§ III). Since both mass estimates scale as the square of the distance to Cen A, this conclusion is independent of the distance.

We can also compare our limit with various models of SN Ia explosions, which predict the production of specific amounts of ^{56}Ni; however, in these cases the distance dependence of the mass limit is important. For example, our limit is inconsistent, for distances less than 5.6 Mpc, with detonation models of SN Ia, which predict the production of ~ 1.4 $M_{\odot}$ of ^{56}Ni. For distances of 3 Mpc or less, the limit is below the estimates of most deflagration models. Independent of the specifics of the explosion, Arnett, Branch, and Wheeler (1985) argued that the amount of ^{56}Ni synthesized must be between 0.4 and 1.4 $M_{\odot}$ for models of exploding white dwarfs. This again is inconsistent with our limit for $D < 3$ Mpc.

While we believe that recent results suggest that the distance to Cen A is 3–4 Mpc, this is still uncertain; therefore, it is possible to interpret our result as a lower limit on the distance rather than an upper limit on the mass of ^{56}Ni.

We should also reiterate that this event differed in some ways from a typical Type Ia supernova, so caution is appropriate in generalizing these results. There is some statistical evidence for significant differences in the light curves of SN Ia (Barbon, Ciatti, and Rosino 1973; Pskovskii 1977, 1984; Branch 1981). The observations of SN 1986G seem to support the thesis that there are significant variations from supernova to supernova within Type Ia (Phillips *et al.* 1987). If SN Ia form a continuum, SN 1986G may be a useful example of a limiting case, e.g., one with substantial unburned or unejected material (Graham 1987*b*).

We acknowledge support for this work under NASA contract S-14513-D. We would like to thank Neil Gehrels for providing us with the results of his gamma-ray transmission calculations. We would also like to thank Greg Jung for modifying his Monte Carlo code to model the GRS geometry, and Mel Ulmer for helpful comments.

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