OSSE Observations of the Cassiopeia A Supernova Remnant[1]

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ABSTRACT

Cas A, the youngest known supernova remnant in the Galaxy and a strong radio and -ray source, was observed by OSSE July 16 - August 6, 1992. Its proximity (3 kpc) and its young age (300 yrs) make Cas A the best candidate among known supernova remnants for detecting ^{44}Ti γ-ray lines. We find no evidence for γ-radiation at 67.9 keV, 78.4 keV, or 1.157 MeV, the three strongest ^{44}Ti γ-ray lines. From simultaneous fits to the three lines our 99 confidence upper limit is 6.61×10^{-5} γ cm^{-2} s^{-1} per line.

INTRODUCTION

Measurement of the amount of ^{44}Ti in a SNR is essential for confirming the accuracy of nucleosynthesis calculations. According to nucleosynthesis theory, ^{44}Ti can be produced in incomplete Si burning during the evolution of a massive star, during explosive Si burning, or during an alpha-rich (low density) freeze-out of nuclear statistical equilibrium. The requirements for Si burning are shown in Fig. 20 of Woosley, Arnett, & Clayton (1973) and Fig. 5 of Thielemann, Hashimoto, & Nomoto (1990). They show temperatures and densities required for incomplete Si burning, normal freeze-out, and alpha-rich freeze-out of Si burning. In the ejected part of a core collapse supernova, only the incomplete and alpha-rich freeze-out of Si burning processes appear to take place. The normal freeze-out of Si burning operates in Type Ia supernova where higher density occurs than in a collapsed massive star (Thielemann, Nomoto, & Yokoi, 1986). Recent calculations of ^{44}Ti production (Woosley & Hoffman 1991 Thielemann, Hashimoto, & Nomoto 1990) show that in order to achieve solar mass fraction of ^{44}Ca, strong alpha-rich freeze-out of Si burning must take place in core-collapse explosions. The ejected amount of ^{44}Ti depends on the mass cut (how much mass falls back onto the neutron star), the pre-supernova composition inside 2 M , and the maximum temperature and density reached during the passage of the shock wave in the ejecta. There are large uncertainties in these parameters, which would be greatly constrained by measurements of ^{44}Ti.

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Table 1: Cas A Characteristics

Location :	l^{II} = 111 °.73 b ^{II} =2 °. 13 (Zorbeck 1990)
Distance :	2.92 kpc (Braun 1985)
Radio and Optical Size :	1.8′ (Dickel et al. 1982)
Radio Emission :	Non Thermal (Synchrotron)
X-ray Emission :	Thermal
Supernova Event :	AD1658 ± 3 (van den Bergh & Kamper 1983)
	1680 observed by J. Flamsteed (Ashworth 1980)
Mass of Ejecta :	≥5 M
Supernova Type :	Type Ib Type II is possible (Fesen & Becker 1991)
Predicted ^{44}Ti mass :	10 $^{-4}$ M
Predicted γ-ray line flux :	3.7× 10 $^{-5}$ γ cm $^{-2}$ s^{-1} (age=312 yrs,
	$_{Ti}$=96yrs, 10 $^{-4}$ M ^{44}Ti, dist=2.8kpc)

Galactic ^{44}Ti γ-ray lines have been sought by the γ-ray spectroscopy experiments on HEAO3 (Mahoney et al. 1992) and the SMM satellite (Leising & Share 1990). Mahoney et al. (1992) obtain a 99 confidence level for 67.9 and 78.4 keV line fluxes of 2× 10 $^{-4}$ γ cm $^{-2}$ s^{-1}. Leising & Share (1993) searching the ten-year data of SMM for the 1.16 MeV line of ^{44}Sc ^{44}Ca decay, place an upper limit of 8× 10 $^{-5}$ γ cm $^{-2}$ s^{-1} from the general direction of the Galactic center at 99 confidence. Their analysis of the upper limits puts some constraint on the galactic supernova rate and the amount of ^{44}Ti produced in supernovae. For example, Leising & Share (1993) find that supernova rates less than 1.5 century $^{-1}$ are consistent with their 1.16 MeV ^{44}Ti line flux upper limit at 5 confidence level. Work combining the record of six galactic supernova in the last millenium and those upper limits of Galactic ^{44}Ti γ-ray line flux is in progress (Hartmann et al. 1992). Cas A is the best known SNR in which to search for this line emission. We summarize some current information regarding the Cas A SNR in Table 1.

OBSERVATIONS and DATA ANALYSIS

The OSSE observation of Cas A was performed during the Compton observatory viewing period 34 (92198 92219). The total observing time was 3× 10 ^{5} seconds. The OSSE spectral analysis technique subtracts background measured in offset pointings of the detectors from the source pointing (Johnson et al. 1993). The emission region in radio and optical wavelengths is well inside the field of view of OSSE. The quadratically interpolated background estimates are subtracted from the source spectrum to obtain a difference spectrum for each 2-minute integration. Detailed description and performance of the OSSE instrument can be found elsewhere (Johnson et al. 1993). The average of all spectra from four detectors over the entire observing period is studied here.

^{44}Ti γ-RAY LINES

Radioactive ^{44}Ti decays to ^{44}Sc, which emits 67.9 keV (100) and 78.4 keV (98) lines, which then decays ($_{12}$ =5.7h) into ^{44}Ca which emits a 1.157 MeV (100) line. The half-life ($_{12}$) of radioactive ^{44}Ti is still uncertain, probably between 46.4 to 66.6 yrs (Frekers et al. 1983 Alburger & Harbottle 1990). If M $_4$ is the mass of ^{44}Ti produced in a supernova in units

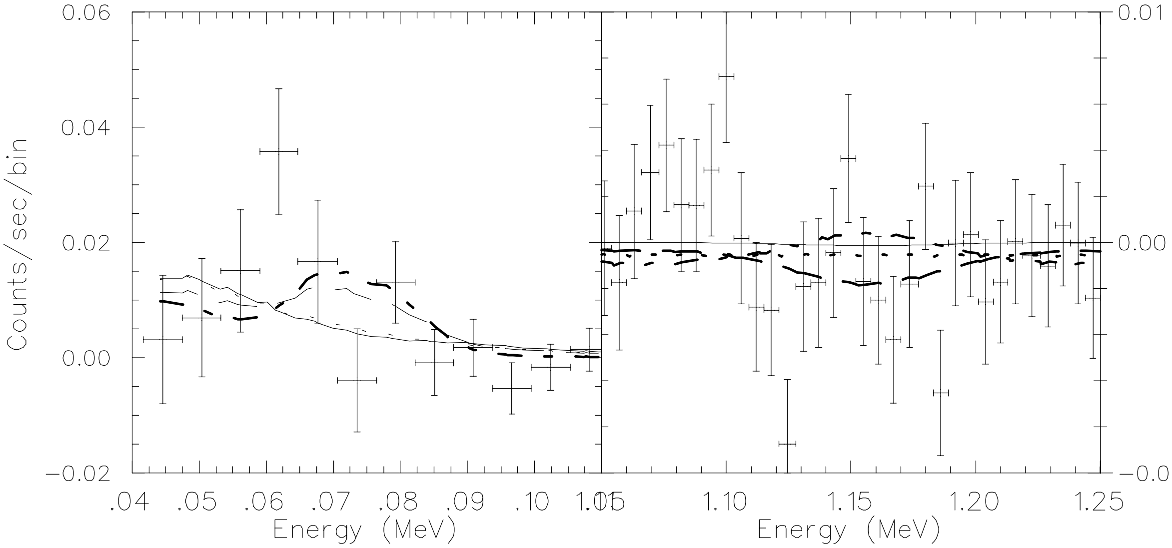

Figure 1: *Average count spectra of OSSE Cas A observation in 0.04 - 0.11 MeV and 1.05 - 1.25 MeV energy ranges and some fits overlayed. The solid line is the best fit to count spectra in the energy range of 0.04 - 1.4 MeV, where an exponential continuum plus the three strongest ^{44}Ti γ-ray lines with fixed flux ratios of 1 : 0.98 : 1 are fitted simultaneously. The best-fit line amplitude is too small to be seen. The dashed line is the best fit to count spectra in the energy range of 0.04 - 0.11 MeV (0.8 - 1.4 MeV) with an exponential continuum and the three ^{44}Ti γ-ray line features fitted simultaneously. For illustration the dashed dotted line is obtained when all three lines are fixed to fluxes of 5 × 10^{-5} γ cm^{-2} s^{-1}. The dotted line is a fit of an exponential continuum only without any line feature to the count spectra of 0.04 - 0.11 MeV (0.8 - 1.4 MeV).*

of 10^{-4} M$_{\odot}$, f_γ the branching ratio of the γ-ray line per ^{44}Ti decay, D_{kp} the distance, and $\tau (= t_{1/2}/ln(2))$ the lifetime of radioactive ^{44}Ti, the γ-ray line flux at earth is

$$F_\gamma = F_0 \, f_\gamma \, M_4 \, \frac{exp(-t/\tau)}{D_{kp}^2} \, \gamma \; cm^{-2} \; s^{-1}, \tag{1}$$

where $F_0 = 0.72/\tau(yr) \, cm^{-2} \, s^{-1}$ is the initial flux (unattenuated) from 10^{-4} M$_{\odot}$ of ^{44}Ti at $D_{kp} = 1$. F_0 ranges from 7.50×10^{-3} to 10.8×10^{-3} as ^{44}Ti half-life ranges from 66.6 to 46.4 yrs.

We see no evidence for continuum emission from Cas A, so to extract line fluxes we fit the count spectra of Cas A observation with various continuum photon spectra plus one or more gaussians at energies of interest. These photon spectra are folded through the four detector OSSE instrument responses and the resulting four count models are least-squares fitted to the respective four detector energy-loss spectra. Since Cas A is currently expanding at a rate of 10,000 km/s, we fix the intrinsic line widths in that fit to 2.5% of the line rest energies. Some results are tabulated in Table 2 and shown in Figure 1.

We find no evidence for ^{44}Ti line emission. The best fit of the 68 keV and 78 keV line fluxes with an exponential continuum between 0.04 - 0.11 MeV gives each a flux of $(+3.05 \pm 4.43) \times 10^{-5}$ γ cm^{-2} s^{-1}. The best fit of the 1.157 MeV γ-ray line flux with 0.8 - 1.4 MeV exponential continuum is $(-5.62 \pm 3.98) \times 10^{-5}$ γ cm^{-2} s^{-1}. The best simultaneous three line

Table 2. Measured Cas A Line Fluxes

Source	Energy (keV)	Continuum (MeV)		Line Flux [a]	χ^2_ν	d.o.f.
^{44}Ti	67.9 & 78.4 [b]	Exp	(0.04-0.11)	(-3.05 ± 4.43)	1.65	44
	1157.2	Exp	(0.80-1.40)	(-5.62 ± 3.98)	0.98	390
	67.9, 78.4, & 1157.2 [c]	Exp	(0.04-1.40)	(-0.54 ± 2.22)	1.05	905

[a] *flux in each line in units of* $10^{-5}\ \gamma\ cm^{-2}\ s^{-1}$.
[b] *Simultaneous fit to 68 keV and 78 keV lines.*
[c] *Setting the ratios of the 68 keV, 78 keV, and 1.157 MeV line fluxes to 1:0.98:1*

fit with 0.04 - 1.4 MeV exponential continuum is (-0.54 ± 2.22)$\times 10^{-5}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for each γ-line. We could also use the 511 keV line from annihilation of ^{44}Sc $\rightarrow$ ^{44}Ca positrons, but since the lifetime of positrons in a SNR is uncertain and depends on many physical parameters, we report here only results using the 68 keV, 78 keV, and 1.1572 MeV γ-lines. The various continuum models are used only to assess the effects of the continuum choice on the measured line fluxes. Although the exponential continuum gives the best fit (marginally), we are not actually seeing any continuum. A constant photon continuum spectrum yields essentially a null continuum, and formally the highest, though still insignificant, line fluxes. To be conservative, we use that fit to quote our final upper limit, which is derived by mapping the variation of χ^2 versus the increasing fixed value of the three line fluxes with all other parameters allowed to vary freely. The 99% confidence upper limit to the flux of each of the three ^{44}Ti γ-ray lines is 6.61$\times 10^{-5}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.

DISCUSSION

The relation between the ^{44}Ti γ-ray line flux from Cas A and the amount of ^{44}Ti is uncertain due to uncertainty in the date of the explosion, the ^{44}Ti lifetime, and the distance to Cas A. The distance is between 2.8 and 3.0 kpc and this causes only about 15% uncertainty in the amount of ^{44}Ti, much smaller than the other uncertainties. If we take the distance = 2.92 kpc (Braun 1985) and the extremes in the age (310-335 yrs) and lifetime (65-95 yrs), we find the initial ^{44}Ti mass in Cas A is constrained to be $\leq$ 1.94$\times 10^{-4}$ M$_\odot$ using the 99% flux limit of 6.61$\times 10^{-5}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. The younger the age and the longer the lifetime of ^{44}Ti are, the stronger is the constraint of the upper limit to the ^{44}Ti mass. The lifetime of ^{44}Ti gives the largest uncertainties. The ^{44}Ti mass limits are consistent with the ^{44}Ti mass ($\sim$ 1$\times 10^{-4}$ M$_\odot$) produced in supernova models of Type Ia, Ib, or II (Woosley & Hoffman 1991; Thielemann, Hashimoto, & Nomoto 1990; Hashimoto et al. 1989; Eisman & Woosley 1988; Nomoto, Thielemann, & Yokoi 1984; Woosley & Weaver 1982).

The COMPTEL experimenters report 1.157 MeV flux from Cas A near 7$\times 10^{-5}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ at 3-4σ statistical significance (Iyudin et al. 1993). This value is marginally consistent with our upper limit. To investigate the possibility that we are subtracting off a signal from a nearby location other than that of Cas A (our 1.157 MeV line flux is formally negative), we measure the 1.157 MeV line flux from each background pointing, using the Cas A pointings for "background" for each. We do this separately for both background pointings, effectively subtracting any flux from Cas A from each. The measured 1.157 MeV line flux from the center of the background field at l^{II} = 116.2° is (-7.21 ± 5.83)$\times 10^{-5}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ and from the other side of Cas A ($l^{II} = 108.0°$), $(+1.19 \pm 4.64) \times 10^{-5}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. If a source were located at the center of one of these background fields the measured flux from it here would be twice the negative amplitude in the Cas A measurement quoted above. Thus we see no evidence for 1.157 MeV flux from anywhere. The lower energy lines confirm this. The simultaneously fitted 68 keV and 78 keV line fluxes from the higher longitude side of background pointing of Cas A, are $(-2.87 \pm 2.82) \times 10^{-5}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ and from the lower longitude side pointing are $(+1.12 \pm 3.39) \times 10^{-5}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ per line. The line fluxes from simultaneously fitting the three strongest ^{44}Ti lines with continuum 0.04 - 1.4 MeV is $(+0.41 \pm 2.81) \times 10^{-5}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ per line from the higher longitude side pointing and from the lower longitude side $(+0.95 \pm 2.53) \times 10^{-5}\ \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. All this suggests that the apparent negative 1.157 MeV flux from Cas A is simply a statistical fluctuation. More observations of Cas A observation are clearly suggested.

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