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Mark D. Leising
Clemson University, lmark@clemson.edu

Gerald H. Share
Naval Research Lab

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GAMMA-RAY LIMITS ON GALACTIC ^{60}Fe AND ^{44}Ti NUCLEOSYNTHESIS

MARK D. LEISING
Department of Physics and Astronomy, Clemson University, Clemson, SC 29634-1911

AND

GERALD H. SHARE
Code 7652, Naval Research Laboratory, Washington, DC 20375
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ABSTRACT

We have searched nearly 10 years of data from NASA's *Solar Maximum Mission* (*SMM*) Gamma-Ray Spectrometer for evidence of γ-ray line emission from the decay of the shorter lived daughters, ^{60}Co and ^{44}Sc, of nucleosynthetic ^{60}Fe and ^{44}Ti. The data are compared with models of the expected signals from the annual scan of the ecliptic by *SMM*. These models include (1) the extended diffuse emission from the many supernovae which should contribute ^{60}Fe over its 2.2 Myr lifetime, and (2) point sources at various locations in the Galactic plane which could be previously undiscovered remnants of supernovae which ejected ^{44}Ti. We find no evidence of Galactic emission from either nucleus; upper limits (99% confidence) are near 8×10^{-5} photons cm^{-2} s^{-1}, for both the 1.17 MeV line from ^{60}Co decay integrated over the central radian of Galactic longitude and for the 1.16 MeV line from ^{44}Sc from points near the Galactic center. The limits on 1.16 MeV flux from longitudes near $\pm 90°$ rise to $\sim 2 \times 10^{-4}$ photons cm^{-2} s^{-1} because the large angular distance to the ecliptic reduces the sensitivity in those directions.

The mass of ^{60}Fe in the interstellar medium today is constrained to be less than 1.7 $M_\odot$. This sets a limit on the current Galactic production rate of ^{60}Fe and of other isotopes coproduced with it, for example, ^{48}Ca and ^{50}Ti. Estimating the current production of these stable isotopes from their solar abundances suggests that there should be about 0.9 $M_\odot$ of ^{60}Fe in the interstellar medium and indicates that ^{60}Fe could soon be detected with a slightly more sensitive instrument. Comparing the estimated production rates of stable isotopes with the γ-ray limits on those of radioactive isotopes allows us to constrain some models of Galactic chemical evolution.

The mass of ^{44}Ti at the Galactic center, for example, is (99% confidence) less than 8×10^{-5} $M_\odot$. This is a quite improbable result viewed in either of two ways. Employing plausible models of Galactic chemical evolution constrained to produce the solar concentration of ^{44}Ca in the Galaxy 4.5 Gyr ago suggests that ^{44}Ca is produced today at the rate (3–4) $\times 10^{-4}$ $M_\odot$ per century. This production rate is consistent with our measurement at 5% confidence only for supernova rates less than 1.5 per century, depending slightly on the actual ^{44}Ti lifetime, and assuming all ^{44}Ca is ejected as ^{44}Ti. Lower rates are consistent with our data, because the implied interval with no supernovae is not so unlikely, but the required higher yields of ^{44}Ti begin to strain current supernova nucleosynthesis calculations. Apart from the solar abundance requirement, we can check the consistency of any combination of supernova rate and ^{44}Ti yield. A Galactic supernova rate of three per century and a yield 10^{-4} $M_\odot$ of ^{44}Ti per event, both very reasonable estimates, are consistent with our data at only 5% confidence. Perhaps the typical yield of frequent supernovae is significantly smaller than this, and the source of most ^{44}Ca is a rare type of high-yield event which has not occurred recently. The isotope ^{44}Ti is probably not a major contributor to interstellar positions.

Subject headings: diffuse radiation — gamma rays: observations — ISM: abundances — nuclear reactions, nucleosynthesis, abundances — supernovae: general

1. INTRODUCTION

The interplay between nucleosynthesis theory and elemental and isotopic abundance data has been tremendously productive (e.g., Weaver & Woosley 1993). However, measured abundances are affected by many complicated astrophysical and chemical processes, so it is often difficult to unambiguously determine nucleosynthesis yields at the production sites. Gamma-ray spectroscopy offers the potential to directly measure individual isotopes at their birthplaces. Radioactive isotopes with decay times short compared to intervals between events which eject them can be measured in individual objects. Isotopes which live long compared to event intervals establish steady state abundances in the interstellar medium. Examples of both of these cases now exist. Radioactive ^{56}Co (Leising & Share 1990 and references therein) and ^{57}Co (Kurfess et al. 1992) have been detected in SN 1987A, confirming specific predictions of supernova nucleosynthesis theory. An unexpectedly large amount of ^{26}Al has been detected in the interstellar medium (Mahoney et al. 1984), and we are still trying to understand its origin. Here we search for evidence of two other promising γ-ray line candidates, ^{60}Fe (Clayton 1971) and ^{44}Ti (Clayton, Colgate, & Fishman 1969).

The isotope ^{60}Fe decays with half-life 1.5 Myr (Kutchera et al. 1984) to ^{60}Co, which then decays to ^{60}Ni with half-life 5.3 yr. In the latter decay, γ-rays of 1.173 and 1.332 MeV are emitted. The isotope ^{60}Fe can be produced in a neutron-rich freezeout from nuclear statistical equilibrium (NSE) (Hartmann, Woosley, & El Eid 1985), in explosive carbon burning (Clayton 1982), and in hydrostatic helium burning (Prantzos 1989). Of order 10^4 supernovae and/or a very large number of mass-losing stars could contribute to the Galactic line emission from ^{60}Fe. There are several interesting parallels between ^{60}Fe and ^{26}Al, including the indication that live ^{60}Fe existed in the early solar system. Shukolyukov & Lugmair (1992) find evidence for live ^{60}Fe, excess ^{60}Ni correlated with Fe, in the meteorite Chervony Kut at level ^{60}Fe/^{56}Fe $\sim 7 \times 10^{-9}$. This is consistent with a 10 Myr delay from the formation of the Allende meteorite, in which there is excess ^{60}Ni corresponding to ^{60}Fe/^{56}Fe $\sim 1.6 \times 10^{-6}$ (Birck & Lugmair 1988), assuming that the ^{60}Ni derives from ^{60}Fe decay in the early solar system. Much work remains to understand these results, but in any case both measurements indicate that ^{60}Fe is ejected by some astrophysical source.

The half-life of ^{44}Ti is not well determined, with measurements ranging from 46.4 to 66.6 yr, although the quoted uncertainties are much smaller than the spread in values (Wing et al. 1965; Moreland & Heymann 1965; Frekers et al. 1983; Alburger & Harbottle 1990). The isotope ^{44}Ti decays to ^{44}Sc with the emission of γ-rays at 68 keV and 78 keV. The ^{44}Sc then decays with half-life 5.7 hr to ^{44}Ca, which then emits a 1.157 MeV γ-ray. The isotope ^{44}Ti is produced primarily in the α-rich freezeout from nuclear statistical equilibrium, that is, when the density is low enough as the reactions fall out of equilibrium that α-particles avoid reassemblage into carbon and are available for capture on heavier nuclei (Woosley, Arnett, & Clayton 1973; Woosley & Hoffman 1991). The site for this can be Type Ia (SN Ia) (Nomoto, Thielemann, & Yokoi 1984; Woosley, Taam, & Weaver 1986) or Type II (SN II) (or any core collapse) supernovae (Woosley, Pinto, & Weaver 1988; Thielemann, Hashimoto, & Nomoto 1990). The Galactic recurrence time of these events is comparable to the ^{44}Ti lifetime, so we expect to be able to see at most a few ^{44}Ti remnants at any given time. Like most Galactic supernovae, these events will not have been detected optically, so we must search the entire Galactic plane to find those, if any, which produce detectable flux at 1.157 MeV.

Mahoney et al. (1982, 1992) used the γ-ray spectrometer on the *HEAO 3* spacecraft to set upper limits on Galactic emission from ^{60}Fe and ^{44}Ti and discussed some of the implications of those limits. We search the nine-year database of the *SMM* Gamma-Ray Spectrometer (GRS), which has roughly a factor of 3 better sensitivity, for evidence of ^{60}Fe or ^{44}Ti emission. Briefly, the search procedure is as follows. The database is divided into 10-day average spectra. Each of these spectra is fit with a simple model to determine the excess counts in the line feature of interest. Because these count rates in general contain background, this time series of line count rates is modeled with a linear combination of the expected variations of relevant background components and the response to a celestial source. The amplitude of the celestial response term is the measured signal.

2. INSTRUMENT CHARACTERISTICS

The *Solar Maximum Mission* (*SMM*) was launched in 1980 February to observe the Sun during the peak of solar cycle 21. The spacecraft operated for most of the time from then until its demise in 1989 December. A problem with the spacecraft attitude control system produced some uncertainty ($\sim 10°$) in the actual pointing direction from late 1980 until it was repaired by Space Shuttle astronauts in 1984. No data were recorded on tape for 5 months before that time. One of seven experiments on board, the GRS, consisted of seven 7.6 cm diameter, 7.6 cm thick cylindrical NaI detectors enclosed in an anticoincidence shield. It had a broad field of view for γ-rays, defined by a 2.5 cm thick CsI annulus aligned with and surrounding the detectors and a 7.6 cm thick CsI disk behind them. Plastic scintillation counters covered the front and rear of the instrument to further reduce the charged particle backgrounds. The spectrometer was sensitive to γ-rays from 0.3 to 8.5 MeV, with energy resolution of 6.4% FWHM at 1.0 MeV. Energy calibration was achieved by means of three ^{60}Co sources near the detectors. The instrument was described in detail by Forrest et al. (1980). The spectrometer was remarkably stable for more than 9 yr. A discussion of its performance can be found in Share et al. (1988).

The axis of the instrument was aligned with the spacecraft axis which was normally pointed at the Sun. Thus the wide field of view of the GRS scanned the ecliptic annually, and the count rate due to a constant source anywhere near the ecliptic plane exhibited a few-month–wide peak each year. It is this annual modulation of celestial sources which has clearly demonstrated the presence of Galactic γ-ray line and continuum emission at other energies (Share et al. 1985; Share et al. 1988; Harris et al. 1990) and which we search for here at the energies of the lines of ^{44}Ti and ^{60}Fe decay.

3. DATA ANALYSIS

Our data base consists of 1 minute (65.536 s) summations of 476 channel energy-loss spectra from 0.3 to 8.5 MeV, each accumulated at least 2.5 hr after any passage through the intense radiation environment of the South Atlantic Anomaly. Data including solar flares, γ-ray bursts, known magnetospheric or man-made background events, and telemetry errors were excluded. A typical GRS background spectrum is shown in Figure 1*a*. All GRS spectra contain the ^{60}Co decay lines at 1.17 and 1.33 MeV which come from an internal energy calibration source and are apparent in the figure. The calibration sources were enclosed in plastic scintillators which detected the β's emitted in ^{60}Co decay and allowed photon events simultaneously detected in the NaI detectors to be tagged as calibration events. When the β-energy was below the threshold of the plastic scintillators the ^{60}Co photons were not tagged and

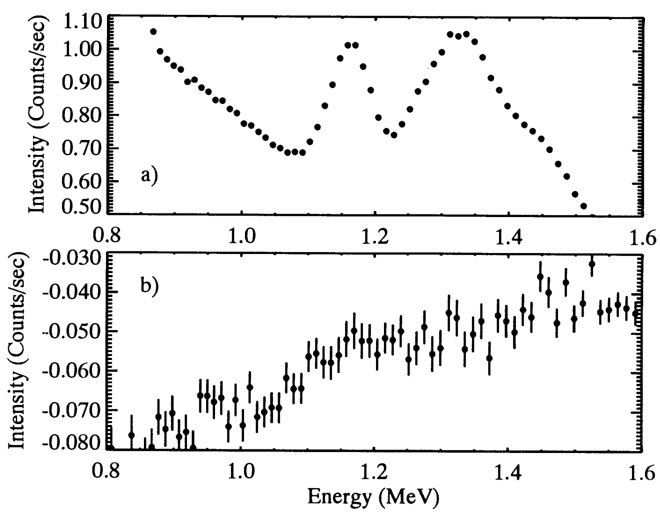

FIG. 1.—*SMM* GRS 10 day average energy spectra in the region of interest. (*a*) The raw energy-loss spectra including all background features. (*b*) The average of orbital subtractions of sky minus Earth-viewing spectra. Note that the spectrum is negative because the Earth contribution is more intense than the sky. The strong background features, including the calibration lines are largely removed by the short-term subtraction.

thus were recorded as valid events in the main detectors. It is ironic that ^{60}Co in the instrument produced strong background lines at precisely the energies at which we search for celestial emission. This requires us to perform significantly more sophisticated data analysis to remove these features.

Figure 2 shows the time variation of the 1.17 MeV line intensity in 10 day averages of all good data. The exponential decay of the calibration sources is apparent, as is a shorter term, $\sim$50 day, variation. Variations of the magnetic field strength and direction due to spacecraft motion might cause changes in the gains of the photomultiplier tubes viewing the calibration source plastic scintillators. This would change the effective thresholds of those detectors, causing a varying fraction of the internal ^{60}Co photons to be tagged. This could be the reason for much of the variation about a simple exponential in Figure 2. We observe a strong correlation of the residual ^{60}Co amplitudes with the spacecraft y-axis magnetic field component, B_y, a strong anticorrelation with B_z, and little or no correlation with B_x. (The spacecraft Cartesian coordinate system is defined such that the $+x$ axis is aligned with the spacecraft axis and points to the Sun and the $+z$ axis is parallel to the projection of the north solar pole on the sky. The plastic detector phototubes are aligned along the x-axis.) Although we can model these effects, there are also several other background lines blended with the 1.17 and 1.33 MeV ^{60}Co features. These include lines at 1.14 MeV (origin uncertain), 1.28 MeV (from radioactive ^{22}Na from spallation of aluminum in the spacecraft), 1.37 MeV (from radioactive ^{24}Na), and near 1.46 MeV (possibly from ^{126}I). All these line features and variations in the underlying continuum affect the 1.17 and 1.33 MeV rates measured by fitting this region of the raw energy-loss spectra, and modeling all of the physical processes involved has proved difficult.

Many of these background lines vary in amplitude on timescales of days or longer, so we can remove their effects by subtracting spectra accumulated nearby in time. We have chosen to subtract spectra taken with the center of the Earth within 72° of the GRS axis ($\equiv$Earth-viewing) from all other spectra ($\equiv$sky-viewing). We accumulate each of these two spectra within each orbit, subtract them normalized by live time, and then average these difference spectra over 10 day periods. A typical such spectrum (sky- minus Earth-viewing) is shown in Figure 1*b*. Residual lines near 1 MeV are greatly reduced in amplitude; however, the ^{60}Co lines are not in general completely removed. The average magnetic field is also in general different in Earth- and sky-viewing portions of an orbit. We also calculate the mean of the differences of the measured magnetic field components along each spacecraft axis, weighted by live time. We fit each 10 day difference spectrum with two different models in the region of interest above 1 MeV. In both cases we are simply fitting the energy-loss spectrum, searching for photopeak (full γ-ray energy loss) excesses.

3.1. *Searching for* ^{60}Fe *Lines*

The model for this search is a power-law continuum from 1.07 to 1.45 MeV plus two Gaussians fixed at 1.173 and 1.332 MeV, with widths fixed at instrument resolution at those energies. The ratio of the amplitudes of these peaks was also fixed at $A_{1.33}/A_{1.17} = 0.93$, which is the ratio measured for the calibration peaks and approximately the ratio expected for an external source emitting both lines with equal intensity. Fitting both lines simultaneously improves the statistical sensitivity by $\sqrt{2}$ over either one individually, and the fit is better behaved than the individual ones. This model has three free parameters, the power-law amplitude and index, and the line amplitude. The last is searched for evidence of ^{60}Fe in the interstellar medium.

The amplitudes of the 1.17 MeV line, derived by fitting both lines with a fixed ratio, and the results averaged over 50 days for presentation are shown in Figure 3. There remains an excess of counts in these lines in the sky minus Earth difference spectra. To determine the celestial contribution to this count rate, we fit the 10 day 1.17 MeV time series with a model consisting of the sum of four terms each multiplied by a free parameter: (1) the expected variation due to a diffuse Galactic source of ^{60}Fe; (2) the calibration source leakage unaffected by local magnetic fields, i.e., an exponential with the ^{60}Co lifetime,

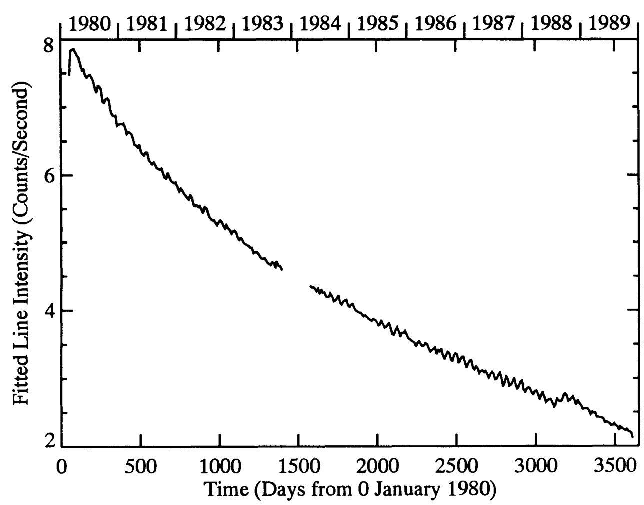

FIG. 2.—The fitted amplitude of the 1.17 and 1.33 MeV lines, fitted simultaneously with a fixed amplitude ratio, in raw data. The short-term variations are possibly due to the variations of the average spacecraft B-field components. The apparent step in the ^{60}Co rates near 3200 days is due to a shield discriminator failure which occurred at that time.

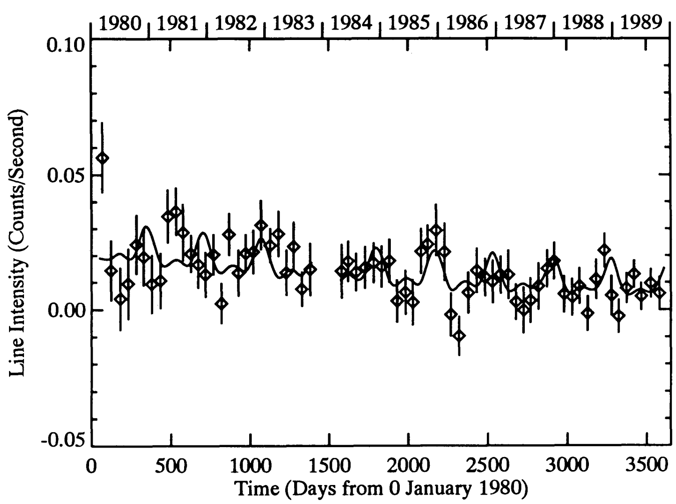

FIG. 3.—The fitted amplitude of the 1.17 and 1.33 MeV lines, fitted simultaneously with a fixed ratio, in background subtracted data. The amplitudes were derived for each 10 days but averaged to 50 days here for presentation. The solid curve is the measured background components (see text) plus a diffuse Galactic signal fixed at 8×10^{-5} photons cm^{-2} s^{-1} rad^{-1}, which is the 99% confidence upper limit.

exp $(-t/7.6 \text{ yr})$; the measured amplitudes of the y- and z-components of the magnetic field times the ^{60}Co exponential; (3) $B_y \exp(-t/7.6 \text{ yr})$; and (4) $B_z \exp(-t/7.6 \text{ yr})$. The model of the diffuse Galactic emission we use is from Leising & Clayton (1985). It was based on CO molecular emission and is similar to the observed distributions of Galactic pulsars and supernova remnants, and thus it is a reasonable distribution for recent supernovae. This analysis is insensitive to the details of the shape of this distribution. Any distribution which peaks in the direction of the Galactic center and whose extent in longitude is $\leq 120°$ will give a similar result for the total measured flux from the central radian of Galactic longitude.

3.2. *Searching for the* ^{44}Ti *Line*

The second model fit to each difference spectrum is a power-law continuum from 1.07 to 1.25 MeV with a Gaussian fixed at 1.157 superimposed. This is used to search for ^{44}Ti decay γ-rays. Because the 1.157 MeV line is only 17 keV below the ^{60}Co peak, it will also be contaminated by the leakage of the calibration source photons. The amplitude of the 1.157 line is displayed in 50 day averages in Figure 4. To extract the Galactic contribution to this line we also then fit the time series with a model consisting of the response to a Galactic source, a simple ^{60}Co exponential, and two exponential terms modulated respectively by the measured B_y and B_z. Because some apparent systematic variations in the 1.16 MeV rate remain, we also add two empirical correction terms to the model. These are the measured rates of other ^{60}Co features, at 1.33 and 2.5 MeV, from independent fits to the same spectra. The 2.5 MeV line is a sum peak from internal coincidences of the two ^{60}Co line. These additional corrections improve the fits significantly and, in principle, the 1.33 MeV term removes any Galactic ^{60}Fe contribution to the measured 1.16 MeV rate.

Because of the ^{44}Ti lifetime, at most a few supernovae could contribute measurable flux. Any Galactic supernovae in the past few hundred years are as yet undiscovered, so we are searching for (a) point source(s) of unknown location in the Galactic plane. Therefore, we fit a series of models, moving the test point-source location around the plane at 20° intervals. It is important to note that these fits are by no means statistically independent, because the instrument angular resolution is much greater than 20°.

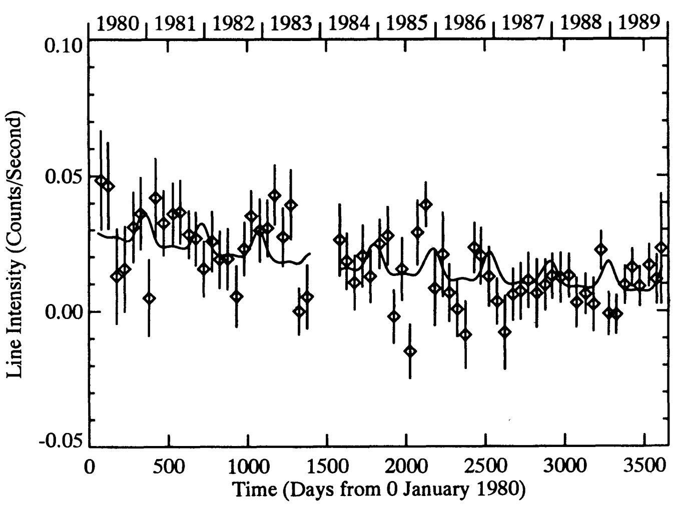

FIG. 4.—The fitted amplitude of the 1.16 MeV line in background subtracted data. The amplitudes were derived for each 10 days but averaged to 50 days here for presentation. The solid curve is the measured background components (see text) plus a point source at the Galactic center with flux fixed at 6×10^{-5} photons cm^{-2} s^{-1} rad^{-1}, which is the 99% confidence upper limit for that point, assuming no other sources.

4. RESULTS

4.1. 1.17 *and* 1.33 MeV *Lines* (^{60}Fe)

The four-parameter fit to the 1.17/1.33 MeV line time series yields $(8.8 \pm 3.2) \times 10^{-3}$ counts s^{-1} at $t = 0$ in the simple exponential, 0.39 ± 0.04 counts s^{-1} Gauss^{-1} and -0.55 ± 0.05 counts s^{-1} Gauss^{-1} at $t = 0$ for the B_y and B_z terms, respectively, and $(2.9 \pm 2.5) \times 10^{-5}$ photons cm^{-2} s^{-1} rad^{-1} of Galactic longitude for the celestial term (averaged over the central radian for the relative distribution discussed above). All uncertainties are 68% confidence limits derived by varying the parameter of interest from its best-fit value with all other parameters free until the χ^2 statistic increased by unity (Lampton, Margon, & Bowyer 1976). This procedure gives the upper extent of the 99% confidence interval for the Galactic flux at 1.17 MeV of 8.1×10^{-5} photons cm^{-2} s^{-1} rad^{-1}. We find no evidence for Galactic ^{60}Fe emission.

4.2. 1.16 MeV *Line* (^{44}Ti)

The best-fit value of the 1.16 MeV flux from a Galactic center point source is $(1.6 \pm 3.2) \times 10^{-5}$ photons cm^{-2} s^{-1}, and the 99% confidence limit is 8.2×10^{-5} photons cm^{-2} s^{-1}. The statistical uncertainty is somewhat larger than in the ^{60}Co fits because only one line was fitted instead of the two with a fixed ratio. Fits performed with a single point source at other locations yield the results displayed in Table 1. Each of these is derived from the results of fits to the same sky minus Earth spectra, so the net exposures are not optimized for each location. Also, because *SMM* scanned the ecliptic, the exposure is maximized for Galactic plane points nearest the ecliptic, e.g., the Galactic center, and thus the increase in the sensitivity at other longitudes. The limits presented in the table are statistical only and include no estimates of systematic uncertainties. We conclude that we have no evidence for a celestial source of 1.16 MeV line emission anywhere in the Galactic plane.

5. DISCUSSION

5.1. *Diffuse Galactic* ^{60}Fe

The Galactic plane 1.17 MeV flux limit above corresponds to a limit of 1.7 $M_\odot$ of ^{60}Fe in the present interstellar medium,

TABLE 1

FITTED POINT SOURCE 1.157 MeV FLUXES

l	Flux[a]	99% Limit	l	Flux[a]	99% Limit
0......	1.4 ± 3.2	8.2	180......	−2.3 ± 3.1	4.3
20......	1.7 ± 3.2	8.5	200......	−1.6 ± 3.1	5.3
40......	1.7 ± 3.3	9.7	220......	−2.1 ± 3.1	5.3
60......	1.7 ± 3.5	9.0	240......	−2.5 ± 3.4	4.5
80......	4.2 ± 4.4	14.0	260......	−2.5 ± 4.1	5.9
100......	6.8 ± 5.5	19.6	280......	−1.1 ± 5.1	9.4
120......	−1.2 ± 5.4	11.2	300......	2.5 ± 4.7	12.3
140......	−7.6 ± 4.4	2.6	320......	1.4 ± 4.1	9.8
160......	−6.0 ± 3.6	2.6	340......	0.6 ± 3.6	8.7

[a] Fluxes are in units of 10^{-5} photons cm^{-2} s^{-1}. Each is derived from the same data under the hypothesis that the given point is the only 1.157 MeV source in the Galaxy.

assuming the aforementioned axisymmetric galactocentric distribution. Although the total *SMM* flux from the central radian of the Galaxy is not dependent on the distribution in the Galaxy, the total mass derived from that flux does depend somewhat on that distribution (e.g., Leising & Clayton 1985). Given the usual assumption of steady state between production and decay, the current rate of synthesis of ^{60}Fe is less than 1.7 $M_\odot$/2.2 Myr. This limit can be viewed in at least two ways. We can constrain the ^{60}Fe yield from a particular type of source, given assumptions about the frequency and uniformity of such sources, and the relative production (or lack thereof) of other sources. We can also compare the limit on the production rate of ^{60}Fe with the production rate of a stable isotope. For example, we can constrain the fraction of stable ^{60}Ni which derives from ^{60}Fe, assuming we can estimate the mass of ^{60}Ni synthesized over the past 2.2 Myr.

5.1.1. *Comparing Stable and Radioactive Isotopes*

It is useful to compare measurements of, or limits on, current synthesis rates to theoretical expectations constrained by solar abundances of stable isotopes. Models of Galactic chemical evolution attempt to describe the evolution of abundances in the Galactic disk given the star-formation rate as a function of, e.g., gas density, the rate of infall of new material onto the disk, and nucleosynthesis yields of stars. The most significant constraints on models of the evolution of abundances of stable heavy isotopes are the solar abundances. These reflect the total (local) Galactic production prior to the formation of the solar system and represent the mass fraction *in the interstellar medium* 4.5 Gyr ago. To use these abundances to estimate current global Galactic production rates we assume that the solar system was typical of the average Galaxy then and that all regions of the Galaxy evolve in a similar way.

We choose to use the analytic chemical evolution models of Clayton (1985) because they are simple plausible models and are easily understood. They assume that the total star-formation rate is proportional to the disk gas mass, with coefficient ω (Gyr^{-1}), and that the disk grows by infall according to the somewhat arbitrarily defined function for the infall rate,

$$f(t) = \frac{kM_{g0}}{\Delta}\left(\frac{t+\Delta}{\Delta}\right)^{k-1} e^{-\omega t}\, M_\odot\ \mathrm{Gyr}^{-1}\ , \qquad (1)$$

where M_{g0} is the initial gas mass, k is a dimensionless parameter, and Δ is a fitting parameter (in Gyr). Choosing $k = 0$ recovers the simple but unrealistic closed box model. Setting $k = 1$, exponential infall, and choosing $\Delta = 0.1$ Gyr and $\omega = 0.3$ Gyr^{-1} describe quite well a number of different astronomical data (Clayton 1985). We use these parameter values for the estimates which follow. These define the mass infall rate which fixes the gas mass and star-formation rates as a function of time.

For such models the gas mass fraction, X, of a stable primary nucleosynthesis product which is not present in the infalling matter is

$$X(t) = \frac{y\omega\Delta}{k+1}\left[\frac{t+\Delta}{\Delta} - \left(\frac{t+\Delta}{\Delta}\right)^{-k}\right], \qquad (2)$$

where y is the yield of the isotope, given as the fraction of the total mass which goes into stars. We take the age of the Galaxy to be 12 Gyr and require that the abundance of a stable isotope grows to the solar value in the gas at 7.5 Gyr. This fixes the yield of that isotope. The production rate of the isotope is given by $y\omega M_g(t)$. We choose M_{g0} to give the Galactic gas mass equal to 10^{10} $M_\odot$ today.

1. ^{60}Fe *Parentage of* ^{60}Ni.—The abundance of ^{60}Ni in solar system matter is $X_\odot$ (^{60}Ni) = 2.0 × 10^{-5} by mass (Anders & Grevesse 1989). This requires the yield of ^{60}Ni to be 1.6 × 10^{-5} and the production rate today equals 5.1 × 10^4 $M_\odot$ Gyr^{-1}, or 112 $M_\odot$ per ^{60}Fe mean lifetime of 2.2 Myr. We therefore constrain the fraction of ^{60}Ni ejected as ^{60}Fe to be less than 1.7 $M_\odot$/112 $M_\odot$, or $\leq$1.5%. We note that the production rate today varies roughly as $(k + 1)$ for a model with a different infall parameter k. Thus, the closed box model, for example, produces ^{60}Ni at only one-half the above rate today. This small fraction of ^{60}Ni from ^{60}Fe is not too surprising, as most ^{60}Ni is probably produced in the α-rich freezeout of NSE (Woosley 1986).

2. *Neutron-Rich NSE,* ^{60}Fe, ^{48}Ca, *and* ^{50}Ti.—As ^{60}Fe is clearly not an important source of ^{60}Ni, it is perhaps more relevant to consider ^{60}Fe production relative to other stable nuclei which are produced mainly by the same processes. Both ^{48}Ca and ^{50}Ti are thought to originate primarily from nuclear statistical equilibrium in matter with a large neutron excess (Woosley 1986). At similar neutron excesses a similar abundance of ^{60}Fe is also produced (Hartmann et al. 1985; see, e.g., their Fig. 2). Therefore, whatever the site where this process operates, if it produces ^{48}Ca and ^{50}Ti it should produce a comparable amount of ^{60}Fe. Again we can use the requirement that Galactic nucleosynthesis produced the solar abundances of the stable isotopes to derive their production rates, and by inference that of ^{60}Fe, today.

The solar abundance of ^{50}Ti is 1.6 × 10^{-7} by mass. In the chemical evolution model described above, the required yield is such that ^{50}Ti is produced today at the rate 410 $M_\odot$/Gyr. This corresponds to 0.90 $M_\odot$ per ^{60}Fe mean lifetime and so we expect roughly this same mass of ^{60}Fe in the interstellar medium today, assuming it is in equilibrium. This is below, but by less than a factor of 2, our current limit. Taking such an argument at face value, we can begin to constrain the current nucleosynthesis rate and chemical evolution models. For example, because production today varies as $k + 1$, models of this class are constrained by our current γ-ray limit to have the parameter $k \leq 3$. Using instead ^{48}Ca, whose solar abundance is 1.4 × 10^{-7}, supports a similar conclusion. It thus also seems likely that a slightly more sensitive broad-field γ-ray spectrometer has a high probability of detecting Galactic ^{60}Fe emission.

5.1.2. *Supernova Ejection of* ^{60}Fe

It has been suggested that a neutron-rich NSE occurs in small regions in both SNIa's and in core collapse supernovae (Hartmann et al. 1985). Either type might eject significant quantities of ^{60}Fe. If we know the frequency of a particular type of ^{60}Fe-producing event in the past few million years, then we can limit the mean ^{60}Fe mass ejected per event. Taking 1.7 $M_\odot$/2.2 Myr, which is 8 × 10^{-5} $M_\odot$ per century, we have

$$M_{\mathrm{ej}}(^{60}\mathrm{Fe}) \leq \frac{8\times 10^{-5}}{R_{\mathrm{SN}}}\, M_\odot\ , \qquad (3)$$

where R_{SN} is the frequency of the supernovae which eject ^{60}Fe, in number per century. Woosley (1991) estimates that SN Ia eject roughly 10^{-4} $M_\odot$ of ^{60}Fe, which is very close to our limit. Reliable estimates for the production of ^{60}Fe in SN II's are not yet available, but models of both types are constrained by this limit. As we are actually limiting the sum of all sources, if we expect that more than one class contributes significant ^{60}Fe, the limit on each is even more constraining.

5.2. *Galactic Point Sources of* ^{44}Ti

Our limits on ^{44}Ti γ-ray fluxes from points in the Galactic plane can also be interpreted in several ways. The most straightforward limit applies to a particular known object, as we discuss in one example below. With regard to otherwise undetected supernovae, we can only evaluate the probability that a given model is consistent with our data. Here, a model must consist of an event rate and the ^{44}Ti mass ejected by each event. In principle the product of these two, which is the current ^{44}Ca production rate, should be constrained by Galactic chemical evolution. One way to proceed is to simulate with Monte Carlo techniques the outbursts in space and time to derive a joint probability for event frequency and ^{44}Ti production per event (Mahoney et al. 1992; Hartmann et al. 1992). We take a simpler approach and estimate ^{44}Ti production based on a few different assumptions. We convert the flux upper limits to lower limits on the time since the latest event of a given yield, and evaluate the probability that we have waited this long as a function of the assumed event frequency of Poisson-distributed events.

We define the following dimensionless quantities: M_{44} is the mass of ^{44}Ti ejected per event divided by $10^{-4}\,M_\odot$, τ_{44} is the (uncertain) ^{44}Ti mean lifetime divided by 100 yr, R is the mean frequency of the relevant type(s) of supernovae divided by 1 per century, and F is the γ-ray flux divided by 10^{-4} photons cm^{-2} s^{-1}. Then from a supernova at distance D, it turns out that numerically the initial value of F is

$$F_0 = \frac{M_{44}}{\tau_{44}}\left(\frac{8.5\ \text{kpc}}{D}\right)^2 , \tag{4}$$

that is, supernovae which eject $10^{-4}\,M_\odot$ of ^{44}Ti at the distance of the Galactic center initially give a flux of 10^{-4} cm^{-2} s^{-1}.

Assuming that all supernovae occur at the distance of the Galactic center, the time to wait for the flux to decay to F, divided by 100 yr, is given by

$$t = -\tau_{44}\ln\left(\frac{F}{F_0}\right) . \tag{5}$$

If the occurrence of supernovae is Poisson-distributed in time, the probability that the true rate $R_t \geq R$, given that we have waited time t without an event, is

$$P(R_t \geq R \mid t) = \exp(-Rt) . \tag{6}$$

We can rewrite this, using equation (5), as the probability that the true rate is $\geq R$ given a flux measurement F,

$$P(R_t \geq R \mid F) = \left(\frac{F}{F_0}\right)^{\tau_{44}R} , \quad F \leq F_0 . \tag{7}$$

Clearly this whole treatment makes sense only if $F \leq F_0$, that is, if we have at least the sensitivity to see the events when they occur. From our *SMM* measurement we have the probability density, $p(F)$, of the flux, which we take to be the Gaussian probability density with mean and variance given by our best-fit value and χ^2 map, respectively, for the Galactic center direction. Then the probability that the true ^{44}Ti supernova rate is $\geq R$ is given by

$$P(R_t \geq R) = \int P(R_t \geq R \mid F)p(F)dF . \tag{8}$$

Now we need to define the yield, or M_{44}, to determine F_0 and evaluate this probability as a function of R. We can use theoretical estimates of the ^{44}Ti yield for various types of supernovae, as we do later, or we can define the yield in terms of the supernova frequency such that the product of the two gives a reasonable value for the current ^{44}Ca synthesis rate.

5.2.1. ^{44}Ca *Production and Chemical Evolution*

It is likely that most ^{44}Ca is produced as ^{44}Ti in nature (Clayton 1982; Woosley 1986). Again we can tie our expectations of current ^{44}Ti production to the requirement that presolar nucleosynthesis produce the solar abundance of ^{44}Ca. The solar system abundance of ^{44}Ca is 1.4×10^{-6} by mass (Anders & Grevesse 1989). Considering exactly the same chemical evolution model described above, the current production rate of ^{44}Ti is required to be $3.6 \times 10^3\,M_\odot$ Gyr^{-1}, or $3.6 \times 10^{-4}\,M_\odot$ per century. The ^{44}Ti mass ejected per event, assuming all ^{44}Ca derives from ^{44}Ti, is then $3.6 \times 10^{-4}\,M_\odot/R$, where R is again the frequency of ^{44}Ti events per century, or in dimensionless units, $M_{44} = 3.6/R$.

Thus, to satisfy the ^{44}Ca nucleosynthesis constraint, F_0 depends on R, and if we assume the latest event was located at the Galactic center, the probability

$$P(R_t \geq R \mid F) = \left(\frac{RF\tau_{44}}{3.6}\right)^{\tau_{44}R} \tag{9}$$

is used in equation (8). This is integrated over all possible fluxes and the integral probability is evaluated as a function of supernova frequency (or recurrence time) in Figure 5, for the two extreme values of τ_{44}. We see that our measurement is consistent at 5% confidence with $R \leq 1.0$, for the most recent value of τ_{44}. We note that the upturn in probability at the highest R is misleading, because at a rate of a few events per τ_{44} centuries, *SMM* will start to see more than only the latest supernova at any one time. In this regard these probabilities are conservative. For example, in the extreme case that there are many events per century, a steady state abundance of $3.6 \times 10^{-4}\tau_{44}$ $M_\odot$ would exist in the Galaxy. This would give a flux compa-

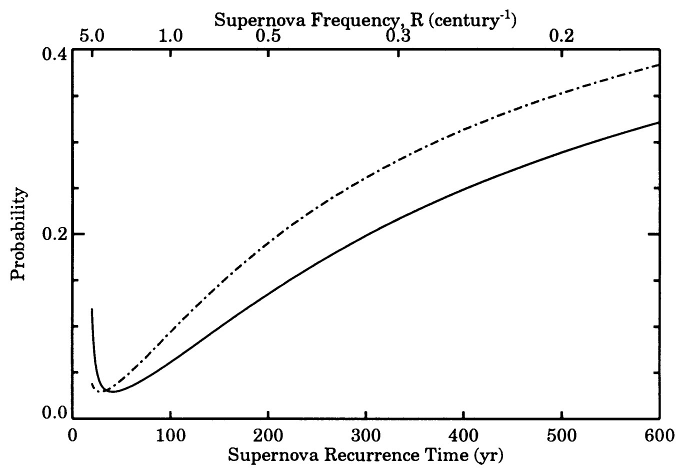

FIG. 5.—The total probability that the mean supernova rate equals or exceeds the value shown, given the *SMM* 1.16 MeV measurement. The calculation assumes Poisson-distributed events and considers only the flux from the latest event, which is assumed to have occurred at distance 8.5 kpc. The ^{44}Ti production per event is a function of the rate, $M_{44} = 3.6/R$, such that the inferred production rate of ^{44}Ca today is maintained. The solid line assumes that the ^{44}Ti half-life is 67 yr ($\tau_{44} = 0.96$), the dot-dash line, 46 yr ($\tau_{44} = 0.67$).

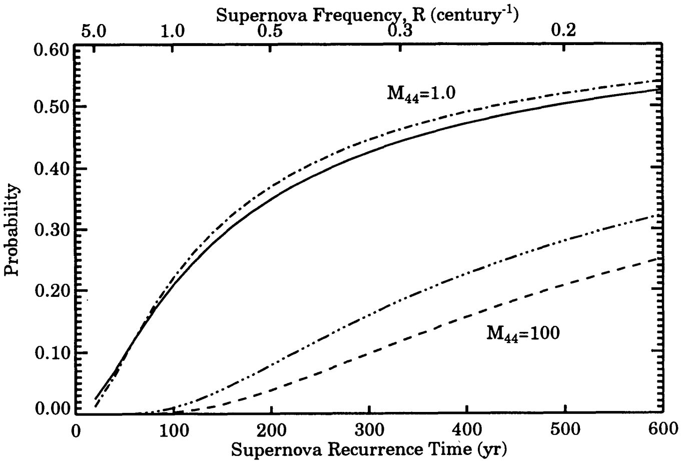

FIG. 6.—As in Fig. 5, except the yield per event is fixed at two different values, $M_{44} = 1.0$ (*solid curve*, $\tau_{44} = 0.96$; *dash-dot curve*, $\tau_{44} = 0.67$) and $M_{44} = 100.0$ (*dashed curve*, $\tau_{44} = 0.96$; *dash–triple dot curve*, $\tau_{44} = 0.67$).

rable to that from ^{26}Al, and would show an obvious signal in our data.

It is interesting that we now most strongly reject what we regarded as the most likely scenario for producing the requisite ^{44}Ca, namely core-collapse supernovae ejecting $\sim 10^{-4}\ M_\odot$ of ^{44}Ti (e.g., Woosley et al. 1988; Thielemann et al. 1990) occurring at $R \sim 3$ (e.g., van den Bergh & Tammann 1991). It is possible ($P \simeq 10\%$) that SN Ia's occurring at frequency $R = 0.5$ and ejecting $M_{44} \simeq 7$ can produce ^{44}Ca at the required rate, although this yield is an order of magnitude higher than current standard estimates (see below). It remains possible that much of the ^{44}Ca has its origin in rare events with very high ^{44}Ti yields.

The assumption that all events occur at distance 8.5 kpc is not valid. Given the (supernova-type dependent) Galactic distribution, the probability that the last event occurred at distance d can be folded in and the probability calculated as above. For center-peaked axisymmetric distributions, the most probable distance is slightly larger than the solar galactocentric distance, and the probabilities are higher that those calculated here. However, for reasonable distributions, the probabilities are only slightly higher. For example, choosing the solar galactocentric distance to be 8.0 kpc instead of 8.5 kpc lowers the probabilities by a similar amount. Also for high rates, greater than 1 per τ_{44} centuries, the increase in probability because the latest event might have been farther than 8.5 kpc is mitigated by the possibility that an earlier event can be closer and possibly even brighter than the latest one. Because taking into account these details requires additional assumptions and does not change the results significantly we choose to omit them here.

5.2.2. *Theoretical* ^{44}Ti *Production*

If we ignore the solar ^{44}Ca nucleosynthesis constraint, or ascribe the bulk of its production to rare high-yield events, we can still constrain the combination of M_{44} and R for typical events as defined by current understanding of supernova nucleosynthesis. Detailed calculations of SN Ia deflagrations (Nomoto et al. 1984; Woosley, Axelrod, & Weaver 1984) show that within a factor of 3, the ^{44}Ti mass ejected is $5 \times 10^{-5}\ M_\odot$ ($M_{44} = 0.5$). Increasing the He content of the white dwarf increases the ^{44}Ti production (Woosley et al. 1986), up to the most extreme case of $M_{44} = 100$. However, these events would not have spectra typical of SN Ia. Calculations of nucleosynthesis in SN 1987A also indicate that SN II can eject $M_{44} \simeq 1.0$ (Woosley et al. 1988; Thielemann et al. 1990), but the exact amount ejected depends on details of the explosion which are not yet modeled. Woosley & Hoffman (1991) show very clearly that the production of ^{44}Ti depends on how much of the matter which undergoes silicon burning does so at low density, resulting in the alpha-rich freezeout of nuclear statistical equilibrium. According to their calculations, almost all of the 0.07 $M_\odot$ of ^{56}Ni from SN 1987A must have come from such a freezeout if it also ejected $10^{-4}\ M_\odot$ of ^{44}Ti.

If we have only a single type of event ejecting M_{44} then the probability that the true rate is $\geq R$ given a limit F is

$$P(R_t \geq R \mid F) = \left(\frac{F\tau_{44}}{M_{44}}\right)^{\tau_{44}R} . \tag{10}$$

We evaluate equation (8) for two values of M_{44}, a "standard" value of 1.0 and the extreme (and necessarily rare) value of 100. These are displayed in Figure 6, again for two values of τ_{44}. We can rule out $R > 2.0$ at 90% confidence and $R > 3.2$ at 95% confidence for $M_{44} = 1.0$. Alternatively, if SN occur at several per century, the ^{44}Ti production must be less than $10^{-4}\ M_\odot$ per event. Again we see that infrequent events, even with very high yields, cannot be ruled out a high level of confidence.

5.2.3. *Galactic Positrons from* ^{44}Ti

The isotope ^{44}Ti has been suggested as a possible contributor to the Galactic positrons which have been observed through their annihilation radiation (Clayton 1973). The 511 keV flux observed by *SMM* (Harris et al. 1990), after subtracting the known positron contribution from ^{26}Al, would require the synthesis of approximately $4 \times 10^{-3}\ M_\odot$ per century of ^{44}Ti, if *all* of the remaining positrons come from ^{44}Ti. This would appear to violate the current ^{44}Ca synthesis rate, which we estimated above to be a factor of 10 lower, but we can treat the probability that it is large enough to produce all the positrons using an equation like equation (9). The production of sufficient ^{44}Ca to account for the annihilation signal is ruled out at 99% confidence for $R > 0.5$. Even if rare events do produce enough ^{44}Ti, they would have to have an unusual history in the Galaxy so as not to overproduce ^{44}Ca. Rather, it is likely that there are other sources of Galactic positrons as well.

5.2.4. ^{44}Ti *Production in* G25.5+0.2

Cowan et al. (1989) have identified the radio source G25.5+0.2 as a very young (25–100 yr) supernova remnant at distance $D \geq 7.2$ kpc. The 99% confidence 1.157 MeV flux limit from this direction is 8.5×10^{-5} photons cm^{-2} s^{-1}. If the remnant is 50 yr old and at $D = 7.2$ kpc, the mass of ^{44}Ti produced is constrained to be less than $1.4 \times 10^{-4}\ M_\odot$. This limit is not in severe conflict with theoretical expectations, although it is less than some calculations give for SN 1987A. In addition to the distance and age uncertainties, there remains doubt as to the true nature of this object (Green 1990; White & Becker 1990; Zijlstra 1991).

6. CONCLUSIONS

We find no evidence in the *SMM* GRS data for Galactic emission of the γ-ray lines of ^{60}Fe and ^{44}Ti decay. Our upper limits are roughly a factor of 3 below previous limits. They are very close to what we expect to see a priori based on a number of theoretical considerations.

We can constrain the mass of material which undergoes a neutron-rich NSE in supernovae at an interesting level based on the limit of 1.7 $M_\odot$ of ^{60}Fe in the present interstellar medium. Plausible models of the Galactic nucleosynthesis history which produce the solar abundances of ^{48}Ca and ^{50}Ti 4.5 Gyr ago predict current production of roughly 1 $M_\odot$ of each per 2.2 Myr (the ^{60}Fe mean lifetime). Because ^{60}Fe is made in comparable amounts at similar neutron excess by this process, we expect a steady state concentration of ^{60}Fe of about 1 $M_\odot$ in the interstellar medium. This is only a factor of 2 below our limit and suggests that this nucleus will be detected in the interstellar medium in the near future. This line of reasoning also calls into question any Galactic evolution models which have current star formation and nucleosynthesis rates higher relative to presolar rates by more than a small factor compared to the model we employ.

Theoretical calculations suggest that roughly 10^{-4} $M_\odot$ of ^{44}Ti is ejected from both core-collapse and thermonuclear supernovae. Such events occurring at the rate of 3–4 per century today are completely consistent with the solar abundance of ^{44}Ca and reasonable Galactic evolution. However, our limit implies that no such event has happened within 8.5 kpc in several decades, which is unlikely for these rates. For lower supernova frequencies we find acceptable, but small, probabilities. These require correspondingly higher ^{44}Ti yields, which are not currently understood theoretically, to produce ^{44}Ca at the required rate. The possibility remains that most ^{44}Ca is produced in very rare events which are copious producers of ^{44}Ti. A candidate, the detonation of a He white dwarf, has been suggested (Woosley et al. 1986; Woosley & Pinto 1988) on other grounds, because all conventional supernova types are thought to produce less than the solar ratio of ^{44}Ca/^{56}Fe (after radioactive decays). If these events do occur, sooner or later we should observe one, recognizable by its unique spectrum (Woosley et al. 1986), in an external galaxy. Even if we ignore the ^{44}Ca nucleosynthesis requirement, we can constrain ^{44}Ti yields from frequent supernovae. For example, we can rule out at $\geq 90\%$ confidence production of 10^{-4} $M_\odot$ for SN at rates ≥ 1.0 per century (which includes current estimates of their frequency; van den Bergh & Tammann 1991; Muller et al. 1992).

Given that on various grounds we expect the flux from ^{44}Ti to approach 10^{-4} photons cm^{-2} s^{-1} from a few points in the Galaxy, we are somewhat surprised that we find none. Because the probability curve for a given rate falls steeply with decreasing flux, even small improvements in sensitivity, as expected from instruments on the *Compton Gamma-Ray Observatory*, will increase greatly the probability of detecting one or more ^{44}Ti supernova remnants. Consequently, if even smaller upper limits on the flux from the whole plane are obtained, it will prove that typical supernovae do not synthesize most ^{44}Ca and reject current estimates of ^{44}Ti synthesis and/or Galactic supernova frequencies.

The Galactic chemical evolution arguments which make the current ^{44}Ti and ^{60}Fe limits so interesting are still somewhat conservative. By comparison, the model we have chosen could not account for the observed radioactive ^{26}Al in the ISM if it all comes from SN II. A similar model with $k = 3$ is required to match the current ^{26}Al/^{27}Al ISM ratio (Clayton, Hartmann, & Leising 1993). That model doubles the current ^{44}Ti and ^{60}Fe production rates over the $k = 1$ model we choose. Therefore, if SN II's make all the ^{26}Al, it is even more puzzling why we do not find any ^{44}Ti remants and why we do not detect ^{60}Fe.

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Note added in proof.—The *Compton Gamma-Ray Observatory* COMPTEL instrument has detected 1.156 MeV emission with flux $(7.0 \pm 1.7) \times 10^{-5}$ cm^{-2} s^{-1} (A. F. Iyudin et al., in Proc. 2d Compton Symp., ed. J. P. Norris [New York: AIP], in press [1994]) from the supernova remnant Cas A ($l = 112°$). This is consistent with our upper limit from that direction, where the *SMM* sensitivity is nearly its worst. In context of this work, it is surprising that such an old (300 yr) remnant is the first detected, unless the rate of ^{44}Ti producing events is quite low.