THE ASTROPHYSICAL JOURNAL, 358:L45–L48, 1990 August 1

LIMITS ON A VARIABLE SOURCE OF 511 keV ANNIHILATION RADIATION NEAR THE GALACTIC CENTER

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Received 1990 March 20; accepted 1990 May 10

ABSTRACT

The Gamma Ray Spectrometer (GRS) on the *Solar Maximum Mission* satellite (*SMM*) has observed a strong Galactic source of 511 keV annihilation radiation from its launch in 1980 to its reentry in 1989. These observations were made during December transits through the instrument's 130° (FWHM) aperture by the Galactic center and are consistent with an extended source having an intensity of $\sim 2 \times 10^{-3} \gamma$ cm^{-2} s^{-1} averaged over the central radian of Galactic longitude. We have searched these data for evidence of the variable Galactic center source of 511 keV line radiation which was reported to have reappeared in 1988 by Leventhal *et al.* The *SMM* data are consistent with, but do not require, a compact source emitting a time-averaged flux of $\sim 4 \times 10^{-4} \gamma$ cm^{-2} s^{-1} during ~ 3 month transits in 1987 and 1988; they are inconsistent (99% confidence level) with a compact source flux in excess of $8 \times 10^{-4} \gamma$ cm^{-2} s^{-1} for each year. We note that the significance of detection of the compact source by previous experiments is strongly dependent on the strength and spatial distribution of the extended Galactic source.

Subject headings: galaxies: The Galaxy — gamma rays: general — nucleosynthesis — radiation mechanisms

I. INTRODUCTION

Annihilation radiation at 511 keV from the direction of the Galactic center was recorded by various balloon-borne experiments in the 1970s (see review by Lingenfelter and Ramaty 1989, hereafter LR, and references therein). Measurements by both balloon- and satellite-borne experiments have continued into the 1980s. The scenario espoused by Lingenfelter and Ramaty is that the radiation is made up of two components: (1) a constant and extended source distributed along the Galactic plane, and (2) a time-varying, and therefore compact, source located within a few degrees of the Galactic center.

Convincing evidence for an extended Galactic component is derived from measurements made by the Gamma Ray Spectrometer (GRS) on NASA's *Solar Maximum Mission* (*SMM*) satellite, coupled with contemporaneous balloon observations. The GRS detected a markedly significant ($\sim 20\ \sigma$) flux of 511 keV line emission during each Galactic center transit through its $\sim 130°$ (FWHM) aperture (Share *et al.* 1988, hereafter Paper I). The time-averaged flux derived from 1980 to 1987 December transits is $(2.3^{+0.5}_{-0.8}) \times 10^{-3} \gamma$ cm^{-2} s^{-1}, averaged over the central radian of Galactic longitude, for various assumed spatial distributions (Harris *et al.* 1990); various systematic uncertainties, including the assumed spatial distribution, produce the large error in absolute flux. This value is higher than, but still consistent with, the value given in Paper I; this increase is due to the larger sample of data and to the utilization of different background corrections. These broad-aperture detections include times in 1981 and 1984 when balloon experiments with $\sim 15°$ apertures did not detect significant fluxes of 511 keV radiation from the Galactic center (see Table 1). We concluded in Paper I that an extended Galactic source could explain this difference.

A similar flux, $(1.91 \pm 0.32) \times 10^{-3} \gamma$ cm^{-2} s^{-1} rad^{-1}, was recorded in 1988 November by the 77° aperture FIGARO balloon experiment (Neil *et al.* 1990), for an assumed extended source along the Galactic plane. Various sources of positrons, including nucleosynthesis of β^+-unstable nuclei produced in supernovae, can account for the density of interstellar positrons required to explain the observed diffuse 511 keV line flux (e.g., Paper I and references therein).

The evidence for a variable source of annihilation radiation from measurements by balloon-borne germanium spectrometers is shown in Table 1. These instruments had similar apertures, ranging from $\sim 15°$ to $\sim 20°$, FWHM. We list both the total flux measured from the Galactic center direction and the inferred excess over a diffuse source with a flat distribution and intensity of $2 \times 10^{-3} \gamma$ cm^{-2} s^{-1}, averaged over the central radian of the Galactic plane. (Note that, with the exception of the UCSD measurement, we have simply used the quoted FWHM for each instrument and a triangular response to estimate the contribution from the extended source. This approximation underestimates the true contribution because the effective instrument response is broader.) These measurements suggest that the compact source was on in the late 1970s, turned off in 1980, and reappeared briefly in 1988. *HEAO 3* originally provided the most compelling evidence for a variable compact source (Riegler *et al.* 1981). However, a new analysis of these data by Mahoney (1988), indicates that the reduction in intensity between the fall of 1979 and the spring of 1980 observations was less significant than originally reported.

The significance of the detection of the variable source is strongly dependent on the assumed strength and distribution of the extended source. For example, the GRIS detections of the variable source in 1988 are at the 4.4 and 7.6 σ levels if no

TABLE 1
HIGH-RESOLUTION OBSERVATIONS OF THE GALACTIC 511 keV LINE

Date	Experiment	Flux ($10^{-4}\gamma$ cm^{-2} s^{-1}) Total	Excess above Diffuse[a]
1977.86.........	Bell/Sandia[b]	12.2 ± 2.2	7.0 ± 2.2
1979.29.........	Bell/Sandia[b]	23.5 ± 7.1	18.3 ± 7.1
1981.89.........	GSFC/CENS[b]	0.0 ± 6.0	−5.2 ± 6.0
	Bell/Sandia[b]	0.0 ± 3.8	−5.2 ± 3.8
1984.89.........	Bell/Sandia[b]	0.0 ± 5.0	−5.2 ± 5.0
1988.33.........	GRIS[c]	7.5 ± 1.7	1.6 ± 1.7
1988.83.........	GRIS[c]	12.1 ± 1.6	6.2 ± 1.6
1989.39.........	UCSD *et al.*[d]	6.5 ± 1.9	−1.9 ± 1.9

[a] Flux $2 \times 10^{-3}\gamma$ cm^{-2} s^{-1} rad^{-1} assumed.
[b] See references in Lingenfelter and Ramaty 1989 (LR).
[c] Leventhal *et al.* 1989; Gehrels *et al.* 1990.
[d] Matteson *et al.* 1989.

extended source was present. This led Leventhal *et al.* (1989) to report that "the compact object has reemerged sometime between 1984 and 1988." If an extended source having a flux of $2 \times 10^{-3}\gamma$ cm^{-2} s^{-1} rad^{-1} is present, the compact source is no longer required during the spring of 1988 observation and is detected at reduced significance, 3.9 σ, during the fall observation. This makes the GRIS measurement consistent with that of Cook *et al.* (1990), which failed to detect a compact source of 511 keV radiation at levels $\lesssim 8 \times 10^{-4}\gamma$ cm^{-2} s^{-1} (95% confidence) from four hard X-ray sources near the Galactic center 18 days prior to the first GRIS observation.

With this same level of extended emission present, the compact source is detected at just over the 3 σ level by the Bell-Sandia experiment in 1977 and just over the 2 σ level in 1979. On the other hand, the combined null measurements in 1981 and 1984 suggest that the extended emission may be weaker than we have assumed in the table. In this *Letter* we report on 9 years (from 1980 to 1988) of Galactic 511 keV line measurements made with the *SMM*/GRS in an attempt to detect emission from the reported compact source.

II. ANALYSIS AND RESULTS

Our current analysis of GRS data follows that described in detail in Paper I. Three-day integrated spectra were accumulated for times in excess of 10,000 s from the last traversal of the radiation belts (the South Atlantic Anomaly or SAA) and with the instrument pointed away from Earth (see Fig. 4 in Paper I). The spectra between 350 and 750 keV were dominated by instrumental radioactivity and were fitted by five Gaussian lines superposed over a smooth continuum (see Fig. 5 of Paper I). The fitted 511 keV intensities exhibit a long-term variation primarily due to production of ^{22}Na (β^+ decay; $\tau_{1/2} = 2.6$ yr) in the instrument housing. Periodic variations ($\sim$24 and 48 days) are due to background features in the spectrum that are modulated by changes in the radiation dosage received in SAA transits and by changes in the average cosmic-ray dose and gamma radiation from Earth's atmosphere (see Fig. 7 and detailed discussions in Paper I and in Kurfess *et al.* 1989). Contamination from extended clouds of positrons emitted from high-altitude Soviet satellites carrying nuclear reactors (Share *et al.* 1989) increased the 511 keV background in 1987 and 1988. A partial failure in a discriminator on the CsI back shield of the GRS caused the background rate at 511 keV to rise by about $\sim$0.4 counts s^{-1} in 1988 August.

Paper I details the evidence that annual peaks in the 511 keV rate are due to a Galactic source of annihilation radiation. The primary purpose of this work is measurement of any intrinsic year-to-year variation of the Galactic source using these annual transits. This was accomplished by (1) modeling the expected response to a transiting Galactic source by convolving the GRS's angular response function with its spatial distribution; (2) applying corrections to the raw 511 keV rates to remove known backgrounds; and (3) fitting the various corrected data sets with the calculated response. We fitted each year of data separately, utilizing a two-term polynomial to model the long-term variation described above (a three-term polynomial was used for the first year of data).

Plotted in Figure 1*a* are the fitted 511 keV rates obtained during the last full transit of the Galactic center in 1988 December (only data taken after the discriminator failure in August are included), after background corrections and the long-term trend have been removed. The solid line shown is the best-fit GRS response to an extended Galactic source following the measured CO distribution (many plausible extended distributions, as well as a point source at the Galactic

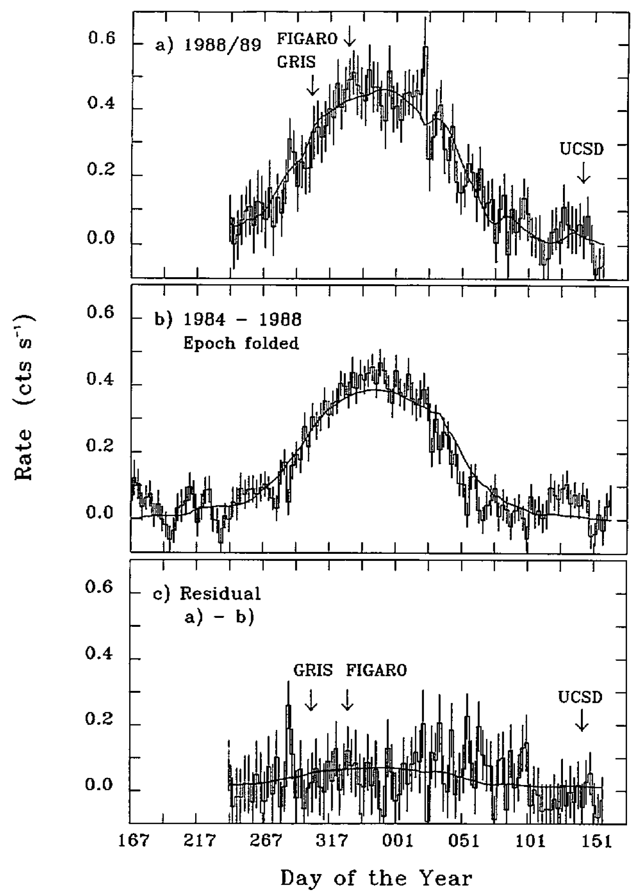

FIG. 1.—Corrected 511 keV line intensities measured by the *SMM*/GRS. Panel (*a*) shows the 1988–1989 transit (beginning in 1988 August), corrected for radioactive contributions using the ^{24}Na line and for atmospheric leakage using the 5–7 MeV γ-ray continuum. Panel (*b*) displays data from 1984–1985 to 1987–1988 transits epoch-folded annually and corrected as in panel (*a*). The rates observed in the 1988–1989 transit in excess of the epoch-folded data are plotted in panel (*c*). The solid lines are the best-fit GRS response to an extended Galactic source following the CO distribution (Leising and Clayton 1985).

center, fit the data acceptably). Most of the background variations from changing exposure to the SAA particles due to *SMM*'s solar orientation and precession of its orbit (Kurfess *et al.* 1989) have been removed by using the 2.75 MeV instrumental background line from ^{24}Na as a monitor. The other important sources of 511 keV background are secondary products of the local cosmic radiation: gamma radiation from Earth's atmosphere (Letaw *et al.* 1989) leaking through the anticoincidence shields and positron production in the instrument. Three different monitors have been used to correct for this background. The data plotted in Figure 1*a* have been corrected using the 5–7 MeV γ-ray continuum and exhibit only small systematic variations relative to the model. We have also applied corrections using the sum of the 4.43 and 6.13 MeV atmospheric lines (from ^{11}B and ^{14}N), and the charged-particle rates from a large plastic anticoincidence counter below the detector. Although the data using these two corrections had larger systematic variations, they have been included in our analysis to support the primary results obtained using the 5–7 MeV continuum correction (e.g., had the time-varying 511 keV source also emitted radiation in this 5–7 MeV band, our measured flux would have been reduced).

Plotted in Figure 2 are the fitted 511 keV line amplitudes for each of the Galactic center transits (no data were accumulated during the 1983 December transit), for both uncorrected and corrected data. The uncertainties reflect both statistical and systematic errors in the fits to the spectra. The data in Figures 2*a* and 2*c* are consistent with statistical dispersion about the mean. In contrast, only 2% and 4% of random samples would have worse dispersions about the mean than data plotted in Figures 2*b* and 2*d*, respectively. This suggests the presence of either additional systematic errors or a variable Galactic source. The 1985 December transit exhibited the largest deviation from the means for the corrected data; this is most evident in data corrected using the charged-particle rates and suggests that it may be due to some systematic error. Even excluding this transit, data corrected using the 5–7 MeV continuum (Fig. 2*b*) are only marginally consistent with a random distribution (7%); this is due to excesses (equivalent to $\sim 3 \times 10^{-4} \gamma$ cm^{-2} s^{-1}) during the last two transits.

In addition to improving the fits to the Galactic transits, the corrections also reduced the mean amplitude of the constant Galactic 511 keV rate (5–7 MeV continuum, 14%; 4.43 + 6.13 MeV lines, 8%; charged particle rate, 6%; and ^{24}Na rate, 3%). The reduction was largest for corrections using the 5–7 MeV rates because of the presence of the diffuse Galactic continuum in this band (see Paper I and Harris *et al.* 1990). Cosmic-ray variations coincident with some of the transits were responsible for the remaining decreases. Absolute fluxes from an assumed point source at the Galactic center can be estimated by dividing the rates plotted in Figure 2 by an effective area of 150 cm^2. Due to a variety of systematic uncertainties, the absolute flux is not known to better than $\pm 25\%$.

We have also used these corrected transits to set a limit on the extent in Galactic longitude of the constant 511 keV emission. Figure 1*b* displays summed 1 yr epochs from 1984–1985 to 1987–1988, corrected and fitted in the same manner as in Figure 1*a*. There is a suggestion of a deficit in flux following the peak of the transit which we attribute to additional attenuation from the satellite which was not included in the adopted angular response of the instrument. The data are also acceptably fitted by simple models of the form $f(l) = K$ for $|l| < \theta$; $f(l) = 0$ for $|l| > \theta$; models of this type with $\theta \gtrsim 65°$ were ruled out (at better than 99% confidence).

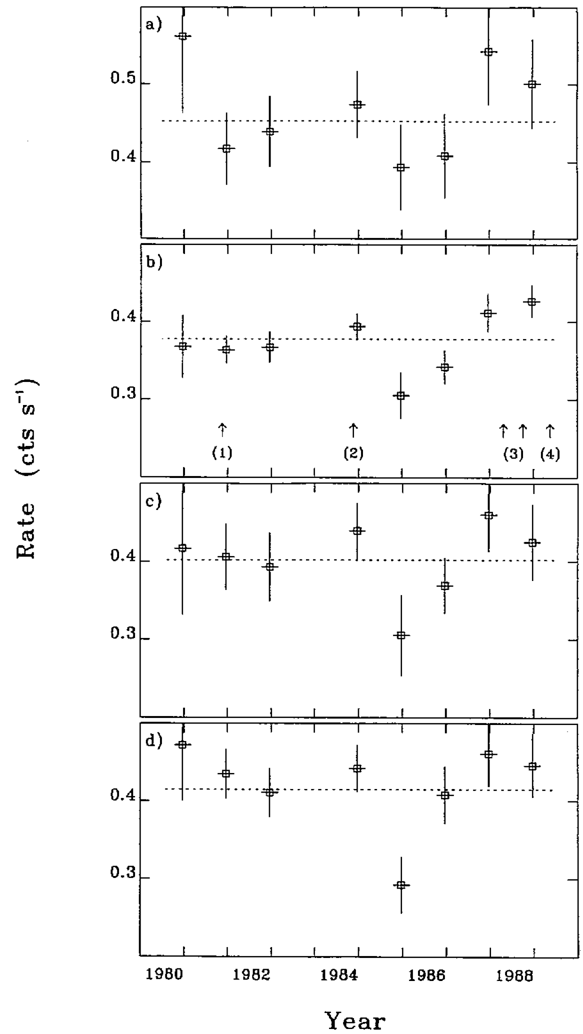

FIG. 2.—*SMM*/GRS measurements of rates from a Galactic center source of 511 keV radiation during transits from 1980 to 1988. Panel (*a*): uncorrected data; panels (*b*), (*c*), and (*d*): data corrected for radioactive contributions and the atmospheric annihilation line using as monitors the 5–7 MeV γ-ray continuum, the sum of the 4.43 and 6.13 MeV lines, and the charged-particle background, respectively. Dashed lines show mean rates. Times of high-resolution balloon-borne measurements are shown in panel (*b*), listed in Table 2, and coded as follows: (1) Bell/Sandia and GSFC/CENS; (2) Bell/Sandia; (3) GRIS; (4) UCSD. For reference we list the values plotted in panel (*b*): 0.368 ± 0.041, 0.364 ± 0.018, 0.367 ± 0.020, 0.394 ± 0.017, 0.305 ± 0.030, 0.342 ± 0.022, 0.412 ± 0.025, 0.427 ± 0.021.

III. DISCUSSION

The *SMM*/GRS observations relating to a variable Galactic center source of annihilation radiation are summarized in Figure 2. We discuss these observations in the context of the evidence for this compact source discussed in § I and detailed in Table 1. These earlier measurements suggest that the compact source was on in the late 1970s, turned off in 1980, and reappeared briefly in 1988. The null balloon observations in 1981 and 1984 occurred well into the Galactic center transits of the *SMM*/GRS in those years (see Paper I). We, therefore, averaged the 511 keV line fluxes observed by the GRS in the 1981–1982 and 1984–1985 transits to obtain the "base level" due to the extended Galactic source. As a measure of the systematic uncertainties, we also estimated the "base level" by

TABLE 2

EXCESS GALACTIC 511 keV FLUXES MEASURED BY *SMM*/GRS ($10^{-4}\gamma$ cm^{-2} s^{-1})

DATA	1987–1988 TRANSIT: BACKGROUND YEARS 1981 + 1984	1987–1988 TRANSIT: BACKGROUND YEARS 1980–1986	1988–1989 TRANSIT: BACKGROUND YEARS 1981 + 1984	1988–1989 TRANSIT: BACKGROUND YEARS 1980–1986
Uncorrected	6.4 ± 5.0	6.9 ± 4.8	3.7 ± 4.4	4.2 ± 4.1
Corrected:[a]				
A	2.1 ± 1.9	3.1 ± 1.9	3.1 ± 1.5	4.1 ± 1.5
B	2.3 ± 3.6	4.6 ± 3.3	0.0 ± 3.7	2.3 ± 3.4
C	1.5 ± 3.2	3.7 ± 3.0	0.5 ± 3.1	2.7 ± 2.9

[a] Data are corrected for radioactive backgrounds using the 2.75 MeV line from ^{24}Na and for leakage of atmospheric γ-rays using (A) the 5–7 MeV continuum, (B) the 4.43 and 6.13 MeV atmospheric lines due to ^{11}B and ^{14}N, or (C) the charged-particle rate as monitored by a large plastic scintillator.

averaging the fluxes observed in the first six transits, even though we have no independent information on the activity of any compact sources during this time period. The excess fluxes observed above these levels by the *SMM*/GRS during the 1987–1988 and 1988–1989 transits are listed in Table 2. All excesses are consistently higher for the "base level" determined from the first six transits; this is in large part due to low flux level recorded during the sixth transit.

There is evidence for 511 keV excess fluxes above the baselines for both the 1987–1988 and 1988–1989 transits. The only significant excesses ($>2\ \sigma$) are in the range of ~ 3 to $\sim 4 \times 10^{-4}\gamma$ cm^{-2} s^{-1} for the 1988–1989 data corrected using the 5–7 MeV gamma-ray continuum (line "A" in the table). Excess fluxes at this level are also consistent with the other corrected sets of data (lines "B" and "C"), which have larger uncertainties. Conservatively, we can also set 99% confidence limits on the flux from a compact source during both the 1987–1988 and 1988–1989 transits; these are $< 8 \times 10^{-4}\gamma$ cm^{-2} s^{-1}. This limit is below the total level observed by the GRIS balloon experiment in 1988 October and suggests that at least 33% of the GRIS count rate came from extended emission along the Galactic plane. This implies a diffuse flux $\lesssim 1.6 \times 10^{-3}\gamma$ cm^{-2} s^{-1} from the central radian of the Galaxy, which is consistent with the *SMM*/GRS observations.

Such an intense flux from the central radian of the Galactic center may not be consistent with both observations of GRIS at $l = 25°$ and the Bell/Sandia and GSFC/CENS experiments in 1981 and 1984 (see Table 1). A broader distribution would provide better agreement. In fact the *SMM*/GRS data are consistent with relatively flat distributions extending up to 65° from the Galactic center (see § II). However, such a broad distribution reduces the diffuse contribution within the GRIS aperture and, therefore, requires that more of the GRIS flux observed from $l = 0°$ would have to come from the compact source. This conflicts with the *SMM*/GRS limits determined from year-to-year variability studies.

Short-term variability of the compact source could explain this discrepancy. We have investigated the possibility that the compact source varies on time scales $\lesssim 3$ days near the time of the GRIS observation. We searched for evidence of variability using two methods: (1) by comparing the 3 day sums with the best-fit model for the transit (Fig. 1*a*) and (2) by subtracting the epoch-folded data in prior years (Fig. 1*b*) from the data in the 1988–1989 transit (see the residuals plotted in Fig. 1*c*). These studies are limited by both statistical and systematic variations (note in particular the systematic fluctuations at the latter part of the transit). There is no evidence of unusual variability at the time of the GRIS observation. The excess fluxes (Fig. 1*c*) in six 3 day accumulations centered on the GRIS flight are (5.0, −4.2, 0.6, 1.9, 5.2, and 0.8) $\pm 6.8 \times 10^{-4}\gamma$ cm^{-2} s^{-1} above background (the error is statistical); the average over these 18 days is $(1.6 \pm 2.8) \times 10^{-4}\gamma$ cm^{-2} s^{-1}.

In summary we conclude that there is good evidence for extended emission of 511 keV line radiation at a level $\sim 2 \times 10^{-3}\gamma$ cm^{-2} s^{-1} from the central radian of the Galaxy. In addition a compact source emitting a flux of $\sim 4 \times 10^{-4}\gamma$ cm^{-2} s^{-1} could have been present during the late fall and winter of 1988. On the other hand, when one considers both the statistical and systematic uncertainties in measuring this level of emission in the presence of such a strong diffuse component, the evidence for a variable compact source is not as compelling as originally presented (Leventhal *et al.* 1989).

We wish to thank Bob Kinzer for assisting in early stages of this work and Jim Kurfess for stimulating discussions relating to the analysis of the *SMM* data. We are indebted to our colleagues Dave Forrest and Ed Chupp at the University of New Hampshire, and Claus Reppin of the Max-Planck Institute for Extraterrestrial Research in Garching, FRG, for their efforts in the design and understanding of this highly successful spectrometer. We also wish to thank Richard Lingenfelter for his detailed comments on this work. This work was supported by NASA under contract S-14513-D.

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