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GRIS DETECTIONS OF THE 511 keV LINE FROM THE GALACTIC CENTER REGION IN 1992

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ABSTRACT

The Gamma Ray Imaging Spectrometer (GRIS) was flown on balloons over Alice Springs, Australia on 1992 April 26 and May 7. A full Galactic center transit (~ 12 hr) was achieved on both flights with the instrument working normally. The electron/positron annihilation line was detected on both flights. The line fluxes and line widths were found to be $(7.7 \pm 1.2) \times 10^{-4}$ and $(8.9 \pm 1.1) \times 10^{-4}$ photons cm^{-2} s^{-1} and 1.3 ± 0.7 and 3.6 ± 1.0 keV, respectively. These results are compared to each other and earlier (1988) GRIS results to produce suggestive evidence for source variability. Near-contemporaneous OSSE/CGRO Galactic center observations indicate that the GRIS results cannot be due solely to a single point source like 1E 1740.7−2942 within a few degrees of the Galactic center. The GRIS 1992 results represent the first time that successive high-resolution balloon measurements have been achieved on a time scale of days.

Subject headings: Galaxy: center — gamma rays: observations — line: profiles

1. INTRODUCTION

For the past 20 years various balloon and satellite experiments have reported 511 keV electron/positron annihilation line radiation from the general direction of the Galactic center (GC). The history of these observations and its implications have been reviewed by a number of workers (Tueller 1993; Skibo, Ramaty, & Leventhal 1992; von Ballmoos 1991; Lingenfelter & Ramaty 1989). The GC region 511 keV line source appears to consist of at least two components, a steady diffuse source extended over many degrees and a point source, probably a stellar mass black hole, located near the GC. The argument for an extended source rests largely on the fact that instruments with increasing fields of view (FOV) report increasing fluxes, whereas the argument for a point source rests largely on the fact that, in the past, narrow-FOV ($\sim 15°$) Ge experiments have reported variable signals (e.g., Lingenfelter & Ramaty 1989). The wide-FOV (130°) gamma-ray spectrometer on the *Solar Maximum Mission* observed the GC 511 keV line source from 1980 through 1989 producing a data set that is consistent with, but does not require the presence of, a variable point source with time-averaged flux $\sim 4 \times 10^{-4}$ photons cm^{-2} s^{-1} (Share et al. 1990). However, the imaging gamma-ray spectrometer SIGMA on the *GRANAT* spacecraft detected a day-long burst of broad (~ 200 keV FWHM) annihilation line radiation from the source 1E 1740.7−2942 located in the Galactic plane but removed by 0°.9 from the GC (Bouchet et al. 1991; Sunyaev et al. 1991). It seems clear now that the GC region is a rich and complicated annihilation line source that continues to remain an enigma. This is an initial report on the latest chapter in this ongoing saga, namely the joint balloon and satellite GC observations in the spring of 1992. In particular, the 1992 GRIS results will be reported and compared to earlier GRIS results and to nearly contemporaneous OSSE observations and some tentative conclusions drawn. The results of additional balloon (HEXAGONE) and satellite (*GRANAT*/SIGMA) observations that were part of the joint campaign are not yet available.

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2. OBSERVATIONS

The GRIS instrument is described in detail by Tueller (1992b). The instrument contains seven of the largest available high-purity Ge detectors cryogenically cooled by a liquid nitrogen dewar. The detectors are surrounded by a thick (15 cm) NaI shield in active anticoincidence which also serves to collimate the FOV of each detector to $\sim 18°$ at 511 keV. It contains ~ 2000 cm^3 of Ge having an effective area ~ 100 cm^2 at 511 keV. The energy resolution of the system is ~ 2 keV at 511 keV. The instrument is an azimuth-over-elevation system and points with an accuracy of a few tenths of a degree. GRIS was flown twice in 1988 and now twice in 1992 over Alice Springs, Australia to observe the GC region which transits very nearly through the zenith over Alice Springs. In each of these flights ~ 12 hr GC observations were achieved. In addition, the 1988 October flight was long enough to allow a 6 hr observation of a point in the Galactic plane 25° west of the GC. A coded mask imaging system for GRIS has been built but not yet flown.

3. RESULTS

Figure 1 shows the results of the 1988 flights (Gehrels et al. 1991). The 1988 May flight (Fig. 1*a*) was the maiden flight of GRIS, and an electronics problem degraded the energy resolution. The problem was fixed for the second flight in October. Nevertheless the GC annihilation line was easily detected on both flights. In the October observation the 511 keV line was resolved in energy for the first time (Fig. 1*b*). A striking decrease in the signal occurred when the telescope was pointed away from the GC (Fig. 1*c*) confirming the fact that most of the emission is well localized near the GC. The residual signal seen in the off-center pointing is believed to be of diffuse origin. The 511 keV line flux derived for each GC flight is listed in Table 1. There is a modest suggestion here, at

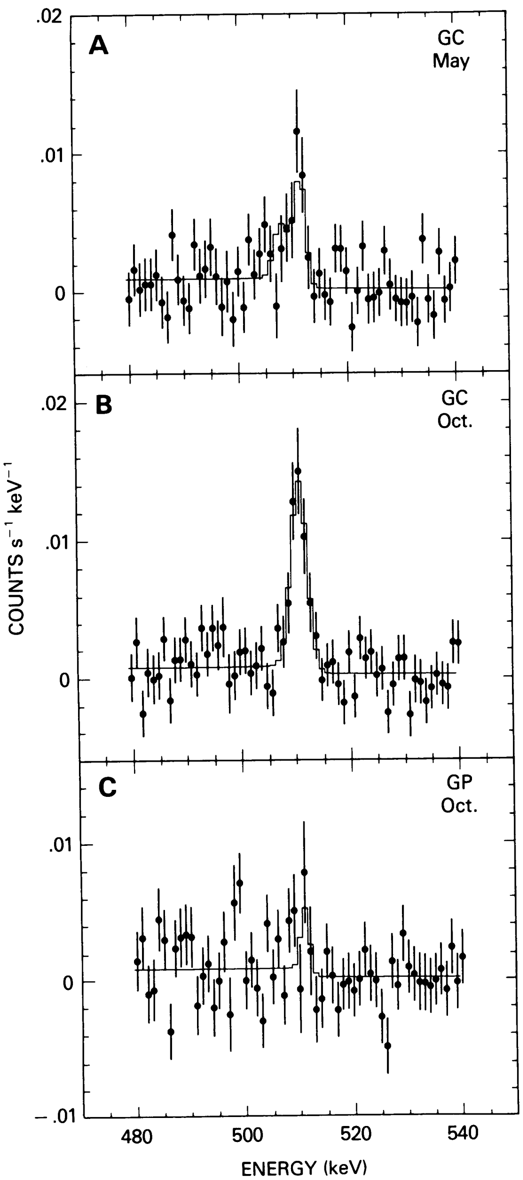

FIG. 1.—Spectra and model fits of the 511 keV line for the 1988 GRIS observations. The Galactic plane observation was made in the direction $l = 335°, b = 0°$.

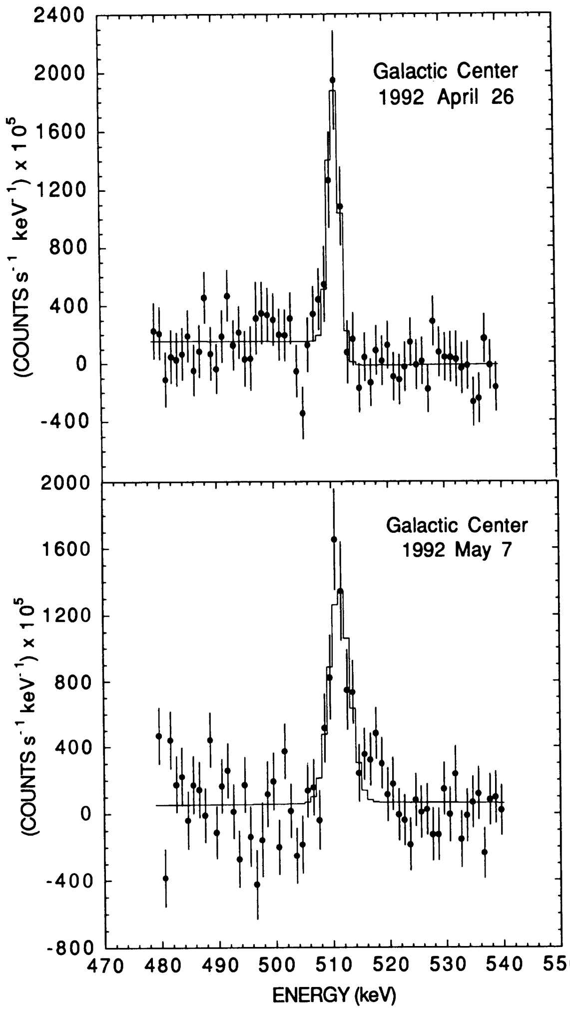

FIG. 2.—Spectra and model fits of the 511 keV line for the 1992 GRIS observations.

the 1.9 σ level, of an intensity variation between 1988 May and October. The tabulated uncertainties are of statistical origin only which are believed to dominate over systematic uncertainties.

The Ge array flown in 1992 differed from that in 1988: on average the detectors were larger, and one of the detectors was isotopically enriched in Ge^{70} (a report on the performance of this detector is given by Barthelmy et al. 1992). Figure 2 shows spectra and model fits for our 1992 April 26 and May 7 flights. The data have been accumulated in alternating ~20 minute target/background pairs with the background taken at the same elevation angle, but the instrument rotated in azimuth so as to maximize the distance from the Galactic plane. The instrument worked well aside from a single detector failure. Complete GC region transits were tracked. Spectra from each

TABLE 1

GRIS GALACTIC CENTER REGION 511 keV LINE RESULTS

Flight	Flux (photons cm^{-2} s^{-1})	FWHM (keV)	Centroid (keV)
1988 May 1	$(7.5 \pm 1.7) \times 10^{-4}$	≤ 3.6	511.46 ± 0.38
1988 Oct 29	$(11.8 \pm 1.6) \times 10^{-4}$	2.9 ± 0.6	510.97 ± 0.26
1992 Apr 26	$(7.7 \pm 1.2) \times 10^{-4}$	1.3 ± 0.7	511.34 ± 0.18
1992 May 7	$(8.9 \pm 1.1) \times 10^{-4}$	3.6 ± 1.0	511.37 ± 0.30
Weighted mean	$(8.8 \pm 0.7) \times 10^{-4}$	2.5 ± 0.4	
Chi-squared	1.65 (3 dof)	2.29 (2 dof)	
Probability	0.18	0.10	

detector were gain-corrected, compressed into 1 keV bins, and summed together into a single composite spectrum for each ~20 minute interval. Background intervals were subtracted from target intervals after scaling for live-time, and the difference was corrected to the mean atmospheric slant-range depth of the observation. These individual flux estimates were then averaged over the entire observation to obtain the final spectra shown in Figure 2. Least-squares curve fitting has been done to obtain estimates of the line fluxes and widths. The solid lines represent model fits to the sum of a Gaussian line plus constant continuum with an adjustable "step" at 511 keV, to allow for a positronium-like (Brown & Leventhal 1987) or Compton (Lingenfelter & Hua 1991) continuum below the line. Considerable evidence exists in the data from both GRIS 1992 flights for a low-energy "tail" on the 511 keV line. This is under study and will be addressed in a future publication. In the past it has usually been interpreted as a three-photon positronium continuum, and its intensity relative to the 511 keV line used to infer a large positronium fraction (Harris et al. 1990). However, a similar tail could be generated by Compton scattering from an attenuating medium or by gravitational redshifts near a compact object. The shape and intensity of these tails should allow us to constrain possible models.

The model fits shown in Figure 2 were derived by multiplying the model photon spectrum by the instrument response matrix and adjusting parameters in the model to minimize χ^2 as described by Tueller et al. (1992b). The response matrix has the effective area times the atmospheric attenuation convolved with the instrument resolution on the diagonal and terms for Compton scattering in the instrument and atmosphere off the diagonal. A Gaussian was used for the instrument resolution function.

There is an apparent bump at ~518 keV in the May 7 spectra. In an attempt to test for the reality of this feature these data were also fitted to the sum of two Gaussians plus constant but unequal continua above and below 511 keV. The F test for three additional parameters (Bevington 1969; Briggs 1991, Appendix) was applied to see if the observed improvement in χ^2 was more than that expected statistically. In fact, the probability of getting the observed improvement statistically was only 0.009. However, at the present time we are not inclined to believe in an astrophysical origin for the feature. Figure 3 shows the sum of our target data and background data plotted separately for the May 7 flight. It is apparent that the 518 keV bump is due to a dip in the background spectra rather than an excess in the target spectra. No such dip is seen in the background taken with other targets on this same flight.

4. DISCUSSION

Table 1 lists our results for the 1992 GC region 511 keV line. The uncertainties indicate 1 σ statistical error bars calculated by finding the deviation of the parameter of interest required to increase the minimum value of χ^2 by 1, with all other parameters free to vary (Lampton, Margon, & Bower 1976). A fundamental question to ask about these results is whether or not line flux or line-width changes were detected between these flights and/or the earlier GRIS flights. A quantitative answer to this question may be obtained by forming weighted means of the two quantities and assuming that GRIS is just detecting statistical fluctuations about these means. One can then calculate χ^2 values for this model and decide if the scatter is reasonable. The weighted means and reduced χ^2 values are listed in Table 1. The probability of getting χ^2 values this large or larger

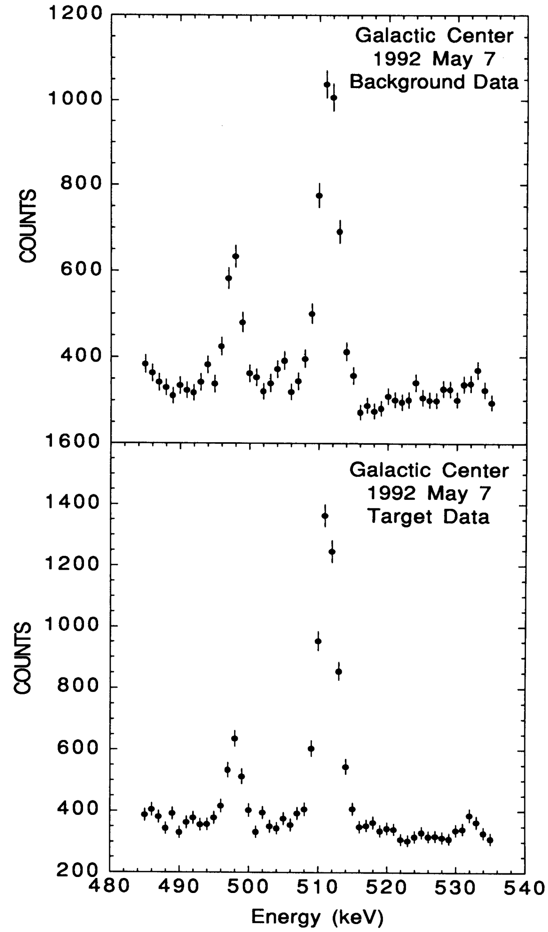

FIG. 3.—Target and background data for the 1992 May 7 GRIS GC region observation. Instrumental lines at 497 and 511 keV are evident.

by chance are 0.18 and 0.10 for the line fluxes and line widths, respectively. *Hence the evidence for source variability (and the inferred presence of a point source) within the GRIS data set alone is suggestive but not compelling.*

The OSSE GC 511 keV line results have been reviewed by Purcell et al. (1993). As of 1992 April, OSSE had viewed the GC region (OSSE FOV is ~4° × 11°) for seven two-week observing periods. The last period ended on 1992 April 23, 3 days before the first GRIS 1992 balloon flight. The OSSE data suggest that they are looking at a steady source within a few degrees of the GC with flux ~2–3 × 10^{-4} photons cm^{-2} s^{-1}, be it a point source, a diffuse source, or some combination. *The obvious conclusion to reach from this result is that the GRIS data cannot be understood in terms of emission from a single point source such as 1E 1740.7−2942 within a few degrees of the GC.* An additional signal is required either from an extended diffuse source seen more effectively with the larger GRIS FOV and/or other point sources out of the OSSE FOV but within the GRIS FOV (Skibo et al. 1992). The variability reported by other narrow FOV experiments in the 1970s and 1980s implies that the known sources such as 1E 1740.7−2942 exhibited greater variability in the past and/or the presence of additional variable point sources near the GC. Indeed one such additional source may already be known (Briggs 1991) and a second suggested (Grindlay, Covault, & Manandhar 1992) based upon observational data.

Since the discovery of a day-long burst of broad annihilation line radiation from the source 1E 1740.7−2942 on 1990 October 13 much attention has been focused on this source as "the" GC positron source. Two groups (Bally & Leventhal 1991; Mirabel et al. 1991) detected a molecular cloud aligned with the source. This led Ramaty et al. (1992) to propose an impulsive model in which approximately day-long bursts of positrons from a compact object are injected simultaneously into a hot, dense accretion disk where they annihilate promptly giving rise to a broad line and into a surrounding cold molecular cloud ($n \sim 10^5$ cm^{-3}) where they slow down and annihilate on a time scale of months giving rise to a narrow 511 keV line consistent with the Ge observations. If the cloud is "patchy" containing more dilute regions where $n \sim 10^3$ cm^{-3} or smaller, this would give rise to a quasi-steady source consistent with the OSSE observations. A compact radio counterpart has been identified (Prince & Skinner 1991; Skinner et al. 1991), and recently Mirabel et al. (1992) employing the VLA have detected bipolar radio jets and lobes emanating from the central object, reminiscent of many AGNs. These workers suggest that the source may be a "microquasar stellar remnant near the GC, which ejects positrons that travel more than a parsec before slowing and annihilating." A crucial piece of observational data remains to be achieved before this exciting prospect can be taken seriously, namely a clear association of the 1E 1740.7−2942 source with a narrow 511 keV line. The GRIS data may contain significant emission from this source, but it must necessarily be convolved with emission from other sources as discussed above. Tantalizing but not yet conclusive evidence for this association exists in the OSSE data set (Purcell et al. 1993). A resolution of this problem may await the launch of proposed Ge experiments on satellites, such as the Integral (Winkler 1991) and GGAPP (Tueller, Gehrels, & Leventhal 1992a), or the flight of more sensitive Ge balloon instruments incorporating coded aperture imaging systems.

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REFERENCES

Bally, J., & Leventhal, M. 1991, Nature, 353, 234
Barthelmy, S. D., Bartlett, L. M., Gehrels, N., Leventhal, M., Tueller, J., & Teegarden, B. J. 1992, in Proc. Compton Symp., ed. M. Friedlander & N. Gehrels (New York: AIP), in press
Bevington, P. R. 1969, Data Reduction and Error Analysis for the Physical Sciences (New York: McGraw-Hill), 158
Bouchet, L., et al. 1991, ApJ, 383, L45
Briggs, M. S. 1991, Ph.D. thesis, Univ. California, San Diego
Brown, B. L., & Leventhal, M. 1987, ApJ, 319, 637
Gehrels, N., Barthelmy, S. D., Teegarden, B. J. Tueller, J., Leventhal, M., & MacCallum, C. J. 1991, ApJ, 375, L13
Grindlay, J. E., Covault, C. E., & Manandhar, R. P. 1992, A&A, in press
Harris, M. J., Share, G. H., Leising, M. D., Kinzer, R. L., & Messina, D. C. 1990, ApJ, 362, 135
Lampton, M., Margon, B., & Bowyer, S. 1976, ApJ, 208, 117
Lingenfelter, R. E., & Ramaty, R. 1989, ApJ, 343, 686
Lingenfelter, R. E., & Hua, X. M. 1991, ApJ, 381, 426
Mirabel, I. F., Morris, M., Wink, J., Paul, J., & Cordier, B. 1991, A&A, 251, L43
Mirabel, I. F., Rodriguez, L. F., Cordier, B., Paul, J., & Lebrun, F. 1992, Nature, 358, 215
Prince, T., & Skinner, G. 1991, IAU Cir., No. 5255
Purcell, W. R., et al. 1993, in Proc. Compton Symp., ed. M. Friedlander & N. Gehrels (New York: AIP), in press
Ramaty, R., Leventhal, M., Chan, K. W., & Lingenfelter, R. E. 1992, ApJ, 392, L63
Share, G. H., Leising, M. D., Messina, D. C., & Purcell, W. R. 1990, ApJ, 358, L45
Skibo, J. G., Ramaty, R., & Leventhal, M. 1992, ApJ, 397, 135
Skinner, G., et al. 1991, A&A, 252, 172
Sunyaev, R., et al. 1991, ApJ, 383, L49
Tueller, J. 1993, in Proc. Compton Symp., ed. M. Friedlander & N. Gehrels (New York: AIP), in press
Tueller, J., Gehrels, N., & Leventhal, M. 1992a, in Gamma Ray Bursts, ed. W. S. Paciesas & G. J. Fishman (New York: AIP), 390
Tueller, J., Barthelmy, S. D., Bartlett, L. M., Gehrels, N., Leventhal, M., Palmer, D. M., & Teegarden, B. J. 1992b, ApJS, submitted
von Ballmoos, P. 1991, ApJ, 380, 98
Winkler, C. 1991, in Gamma Ray Line Astrophysics, ed. P. Durouchoux & N. Prantzos (New York: AIP), 483