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GRIS OBSERVATIONS OF THE GALACTIC CENTER

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The 511 keV positron annihilation line source in the Galactic Center (GC) region has reappeared after being in a quiescent state since the early 1980's. We report observations by the GRIS balloon instrument showing that the 511 keV line has returned to an intensity level similar to that seen in the 1970's. We have resolved the line width for the first time and made a measurement of the spatial extent of the emission along the galactic plane. GRIS is a high-resolution germanium (Ge) spectrometer with a 17° field-of-view. Eleven hours of data were obtained from GC pointings on balloon flights over Australia on 1 May 1988 and again on 29 October 1988. An additional seven hours were obtained on 30 October 1988 from a point in the galactic plane (GP) 25° west of the center (l = 335°, b = 0°). Preliminary results for the line fluxes (in units of 10^{-4} ph cm^{-2} s^{-1}) from the GC are 9.8±1.9 in May and 12.3±1.6 in October, and from the GP are 2.4 ± 1.6 (1 sigma statistical errors). The flux for the off-center pointing is significantly lower than that for the GC pointings and indicates that the dominant emission is narrowly concentrated at the center. The line width for the GC pointing in October is 3.6±0.5 keV, which implies a temperature for the annihilation medium of $\leq 10^5$ K. A step in the continuum emission at 511 keV is found in both the GC and GP data. The step may be due to orthopositronium three-photon annihilation for the GC, but is too large relative to the 511 keV line for the GP to be simply explained by positronium.

INTRODUCTION

Positron annihilation radiation from the the GC region was first observed by Haymes et al. (1975) in 1970 with low-resolution NaI detectors. The first unequivocal identification of the 511 keV line was made in 1977 by Leventhal et al. (1978) using high-resolution Ge detectors. A summary of all 511 keV GC line measurements is plotted in Figure 1, with references given in reviews by Ramaty and Lingenfelter (1987) and Leventhal (1987). The Bell/Sandia (Leventhal et al. 1980, 1982, 1986), JPL (Riegler et al. 1981, 1985) and Goddard (Paciesas 1982) observations with relatively narrow (≤35°) fields of view show that the GC source turned off in 1980 and did not reappear until after 1984. The positive measurements (Share et al. 1988) during the 1980's by the wider field-of-view gamma-ray instrument on the Solar Maximum Mission (SMM) are evidence for an additional diffuse component to the emission.

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We present in this paper results from new observations of the GC showing that the 511 keV line has reappeared. The data were obtained during the first two flights of a new-generation Ge balloon instrument called the Gamma-Ray Imaging Spectrometer (GRIS). Preliminary results are given by Leventhal et al. (1989).

INSTRUMENT

The GRIS instrument (Teegarden et al. 1985; Tueller et al. 1988), shown schematically in Figure 2, is a balloon-borne high-resolution spectrometer operating in the 20 keV to 8 MeV energy range. It consists of an array of seven Ge detectors (total volume = 1560 cm^3) cooled to ~90 K by liquid nitrogen. The detectors are surrounded by 396 kg of NaI in active anticoincidence. Aperture holes in the shield above each Ge detector define a 17° FWHM field of view at 511 keV. The detector effective area at 511 keV is ~85 cm^2 and the resolution is 1.8 keV FWHM. The payload launch weight is 1680 kg.

The flight gondola shown in Figure 2 provides a pointed platform for the instrument. An azimuth-over-altitude digitally controlled pointing system orients the instrument using a magnetic reference to an absolute accuracy of 0.3°. Star camera and sun sensor systems are used to confirm pointing performance in flight. The pointing and spectroscopic performance of the instrument were verified during each flight by observations of the Crab. The measured Crab spectra are consistent with previous observations.

OBSERVATIONS

GRIS was flown twice from Alice Springs, Australia in 1988. The first flight was on 1 May 1988 during which the Galactic Center ($\alpha = 17^h\ 42^m$, $\delta = -29°\ 0'$) was observed for 11 hours and SN 1987A for 12 hours. The second flight was a classic 2-day (44 hours at float) flight on 28-30 October 1988. The observations were as follows: the GC for 10 hours, a point in the GP 25° west of the GC ($\alpha = 16^h\ 22^m$, $\delta = -48°\ 42'$; $l = 335°$, $b = 0°$) for 7 hours, and SN 1987A for 24 hours (2 passes). Spectral lines from ^{56}Co decay were detected during the SN 1987A observations as reported by Teegarden et al. (1989) and Tueller et al. (1989). The average float depth, d, and slant range, s, (in g cm^{-2}) for the GC and GP observations were: 1 May GC d=4.8, s=7.0; 29 October GC d=5.7, s=7.6; 30 October GP d=4.3, s=5.5.

Data were accumulated in alternating 20 minute target-background segments, with some background segments taken before and some after the target segments. For background the telescope was maintained at the same zenith angle but rotated in azimuth so as to minimize the extent of the GP in the field of view. Azimuth offset angles varied from 200° to 240°. Background fields were examined to make certain that no gamma-ray sources were contained in them.

DATA ANALYSIS

Counts in each detector were accumulated during each observing segment in channels 0.25 keV wide. Spectra from each detector were then gain corrected using lines at 198, 511 and 1461 keV and compressed by a factor of ~4 into 1 keV bins. The gain corrected spectra from the seven detectors were summed together. After division by segment accumulation time, background spectra were subtracted from target spectra. The 511 keV line in the background spectrum had an intensity of 0.17 cnts s^{-1} (compared with

0.06 cnts s^{-1} for the astrophysical line) and a width of 2.9 keV. The line is broader than the instrument resolution (and the width of other adjacent background lines) of 1.8 keV at 511 keV. The target-background differences were divided by livetime fraction (~0.9), atmospheric transmission and total effective area, to form flux estimates. Different target-background pairs were weighted inversely according to variance and averaged to obtain a final flux estimate and variance.

For model fitting of the spectra, the May and October data were treated differently in this preliminary data analysis. For the May flight, unanticipated difficulties related to very-high-energy cosmic-ray events degraded the energy resolution to ~5 keV at 511 keV and distorted the line shape, thus frustrating attempts to determine the line profile. Nevertheless, the net flux spectrum formed as described above contains a highly significant feature at 511 keV. To evaluate the flux in the feature, the continuum net flux values determined in the intervals 464-503 keV and 517-556 keV were interpolated inwards to 511 keV and subtracted from the net flux in the interval 504-515 keV.

For the October flight the resolution problem was fixed. We have analyzed these data in the vicinity of the 511 keV line by fitting with various models. The energy window used was 470-550 keV, and the models used included a flat continuum with and without a step at 511 keV to allow a positronium-like continuum below the line and with one and two Gaussian lines to allow for a two-component line shape. Fits were derived by transforming the model photon spectrum through a matrix which contains the detector resolution and off-diagonal terms. The off-diagonal response is due to Compton-scattered events in the detectors which are not rejected by the shield, and to scattering in the atmosphere. The terms are small and have only minor effects on the fits. Nonlinear fitting to the line parameters was performed using the CURFIT program from Bevington (1969). One sigma errors were calculated by finding the deviation of a parameter which increases the minimum value of chi-square by 1, with all other parameters free to vary (Avni 1976).

RESULTS

The spectra between 350 and 700 keV for the May and October GC observations and for the October GP observation are shown in Figure 3. An intense positron annihilation line at 511 keV is seen in both GC spectra, but is virtually absent from the GP spectrum. Our best fits to the October data sets in the 511 keV vicinity are shown in Figure 4. Both October spectra are well fit by a single Gaussian line plus a flat continuum with a step at 511 keV. For the GP spectrum the line statistics are poor so we reduced the number of parameters in the fit by constraining the line centroid at 511.0 keV. Chi-square for the two fits are 74 for 75 degrees of freedom for the GC data and 73 for 76 degrees of freedom for the GP data.

The results of the May 511 keV line flux integration and the October fits are listed in Table I. The line flux for the May and October GC observations are statistically consistent with each other, giving an average line flux for this period of $(11.3\pm1.2)\times10^{-4}$ ph cm^{-2} s^{-1}. This is similar to the flux levels seen in the 1970's and shows that the positron annihilation source in the GC region has re-emerged after disappearing in 1980 (see Figure 2). The line intensity is much reduced in the GP pointing, which at $l=25^\circ$ just excluded the GC from the 17° GRIS field of view. This implies that the dominant emission from the GC at the time of the GRIS observation was not the diffuse component measured by SMM (Share et al. 1988), but rather a narrowly distributed emission or point source in the GC region.

TABLE I

GRIS GALACTIC CENTER AND PLANE RESULTS

1 MAY 1988

511 keV LINE FLUX	$(9.8\pm1.9) \times 10^{-4}$ ph cm^{-2} s^{-1}

29 OCTOBER 1988 - GALACTIC CENTER

511 keV LINE FLUX	$(12.3\pm1.6) \times 10^{-4}$ ph cm^{-2} s^{-1}
LINE CENTROID	511.22 ± 0.28 keV
LINE WIDTH (FWHM)	3.6 ± 0.5 keV
3-γ Ps CONTINUUM FLUX *	$(4.4\pm1.7) \times 10^{-3}$ ph cm^{-2} s^{-1}
Ps FRACTION *	95 ± 11 %

30 OCTOBER 1988 - GALACTIC PLANE

511 keV LINE FLUX	$(2.4\pm1.7) \times 10^{-4}$ ph cm^{-2} s^{-1}
LINE WIDTH (FWHM)	5.2 (+4.2,-3.9) keV
3-γ Ps CONTINUUM FLUX *	$(3.2\pm1.6) \times 10^{-3}$ ph cm^{-2} s^{-1}

* Assuming continuum step at 511 keV is due to positronium three-photon decay

We have resolved the GC 511 keV line for the first time. The width of 3.6 ± 0.5 keV FWHM (compared with an instrument resolution of 1.8 keV at 511 keV) is broader than the value 1.6 (+0.9,-1.6) keV obtained by HEAO 3 (Riegler et al. 1981) in Fall 1979. The GRIS measurement corresponds to thermal broadening in an annihilation medium of 10^5 K or a velocity distribution of the emitting region of 2×10^8 cm s^{-1} FWHM.

Interpreting the step in the continuum at 511 keV as due to three-photon emission from orthopositronium annihilation, we have calculated the integral flux in the three-photon component as listed in Table I. The positronium fraction (see, e.g., Brown and Leventhal 1987) is given by $f = 4\, I_{3\gamma} / (4.5\, I_{2\gamma} + 3\, I_{3\gamma})$ where $I_{3\gamma}$ is the three-photon flux and $I_{2\gamma}$ is the 511 keV line flux. The GC observation gives a $95\pm11\%$ positronium fraction. For the GP observation however, the flux in the three-photon continuum is too high to be explained by even 100% Ps annihilation. Assuming the step in the GP continuum is due to three-photon annihilation, the three-photon flux is more than an order of magnitude larger than the 511 keV line flux, compared with a maximum of a factor of 4.5 for 100% Ps annihilation. Note, however, that both the GP line flux and three-photon continuum are each $\leq2\sigma$ measurements. Also, the fit to the three-photon continuum is sensitive to the assumed shape of the underlying continuum. We have assumed a flat continuum spectrum for this analysis, but a better assumption would be a continuum shape based on the data above and below the line region. Analysis is in progress to fit the entire spectrum and determine more accurate three-photon continuum fluxes.

DISCUSSION

The GRIS data, when coupled with previous observations of the GC 511 keV line, strongly suggest that a time-variable source of positrons is located near the GC. Our observation of the re-emergence the line after >4 years absence may be the first evidence for a periodic source. The 511 keV emission is intense. For an isotropic source at a distance of 8 kpc, the line flux corresponds to a luminosity of ~7×10^{36} erg s^{-1} (2000 $L_\odot$ in a single spectral line) and requires ~4×10^{42} annihilations per second. If all of these annihilations occur via the bound Ps state then these numbers are four times larger, with the additional luminosity appearing in a Ps continuum.

An interesting aspect of the GRIS data is the similarity between the GC and GP three-photon continuum fluxes while the line fluxes are so different. This suggests a common origin for the continuum. Ramaty and Lingenfelter (1989, see also Lingenfelter and Ramaty 1989) have recently proposed a two-component model of the GC and GP positron annihilation radiation that may provide an insight into this aspect of the GRIS data. One component is a distributed source of positrons (probably from supernovae) that annihilate in the warm component of the interstellar medium producing a flux of ~1.5×10^{-3} photons cm^{-2} s^{-1} rad^{-1} in the direction of the GC (derived from SMM) with a longitude distribution along the GP similar to that of the observed >70 MeV gamma rays. Annihilation occurs predominantly via Ps for this component producing a three-photon continuum flux of $(7.3 \pm 1.8) \times 10^{-3}$ ph cm^{-2} s^{-1} rad^{-1} (weighted mean of all previous orthopositronium measurements). The 511 keV line has a width of <2 keV based on the ~10^4 K temperature of the warm interstellar medium. The second component is a time-variable point source of positrons at or near the dynamical center of the galaxy. The source is likely to be a <10^3 $M_\odot$ black hole producing positrons by photon-photon interactions in a hot accretion disk. The three-photon continuum is absent for this component due to annihilation on dust or the photoionization of orthopositronium by UV radiation. The three-photon continuum is therefore due solely to the distributed source. The 511 keV line for the black hole may be narrow if the annihilation is on dust or may be broadened by thermal or bulk motion of the annihilating medium for the photoionized orthopositronium.

The GRIS data are consistent with the Ramaty and Lingenfelter model, although the agreement is at the limits of the statistics. The distributed source would give a 511 keV line flux at 25° west of the GC in the GRIS 17° FWHM aperture of ~4.1×10^{-4} ph cm^{-2} s^{-1} (Ramaty and Lingenfelter 1989) and a three-photon continuum flux of $(2.0 \pm 0.5) \times 10^{-3}$ ph cm^{-2} s^{-1}. This is to be compared with our measurement of $(2.4 \pm 1.7) \times 10^{-4}$ ph cm^{-2} s^{-1} for the line and $(3.2 \pm 1.6) \times 10^{-3}$ ph cm^{-2} s^{-1} for the continuum. The measured line is low and the three-photon continuum is high, but both are within statistics. The strongest disagreement is between the predicted three-photon continuum flux for the GC pointing of $(2.2 \pm 0.5) \times 10^{-3}$ ph cm^{-2} s^{-1} compared with the measurement of $(4.4 \pm 1.7) \times 10^{-3}$ ph cm^{-2} s^{-1}.

The Ramaty and Lingenfelter model would imply that the step in the continuum for the GRIS GP data is in fact due to the orthopositronium three-photon continuum, and that the unphysical ratio of continuum to line flux is caused by statistical fluctuations. Another possibility is that the step in the continuum is due to Compton scattering of line photons emerging from an embedded source (Forrest 1982, Bildsten and Zurek 1988). There are also non-black hole models for the GC point source. Recently, a tentative identification of the positron source with the X-ray pulsar GX1+4 was suggested by McClintock and Leventhal (1989), based on the similarity of the X-ray and gamma-ray light curves over 18 years, the positional agreement of the sources and the unusual properties of GX1+4.

CRITICAL OBSERVATIONS FOR GRO

The new GRIS observations of positron annihilation radiation from the GC suggest several critical observations for GRO. The intense 511 keV line observed during the 1970's that disappeared in 1980 is now known to be episodic. A long term study of the time variability of the source is required for which the extended GRO mission is ideally suited. The important determination of the source location and possible identification with a known X-ray source can be done early in the GRO mission by both the OSSE and COMPTEL instruments.

The nature of the distributed source can be studied by the planned GRO GP scan. If the low value for the GP 511 keV line flux measured by GRIS is accurate and applies to other regions of the GP, then the fraction of this emission due to ^{26}Al decay is larger than previously thought. Based on the the HEAO-3 value for the 1809 keV line flux of 4.8×10^{-4} ph cm^{-2} s^{-1} rad^{-1} (Mahoney et al. 1984), the predicted 511 keV flux from ^{26}Al decay for the GRIS GP observation is $(0.5\text{-}2.1) \times 10^{-4}$ ph cm^{-2} s^{-1} depending on the positronium fraction, compared with the measured $(2.4 \pm 1.7) \times 10^{-4}$ ph cm^{-2} s^{-1}. The distributed 511 keV line emission may be due almost entirely to ^{26}Al decay. GRO will be able to measure the 511 keV line to 1809 keV line ratios along the GP and study this question in detail.

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GALACTIC CENTER 511 keV LINE LIGHT CURVE

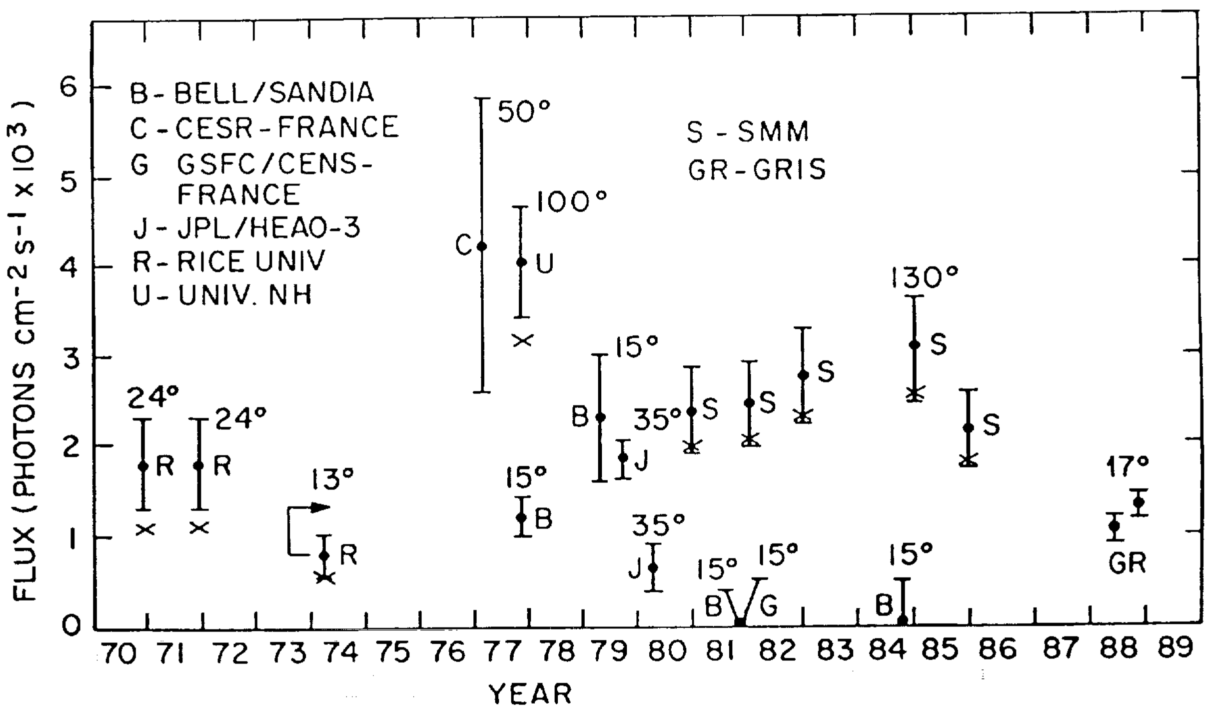

FIGURE 1

Observations of 511 keV line emission from the direction of the GC. The field of view of each instrument is indicated. The X's represent line flux corrections made for an assumed Ps fraction of 0.9. The NaI instruments unavoidably include some three-photon Ps continuum in the line. The 1974 Rice measurement was made in a direction ~5° off the GC and needs to be corrected as indicated for a point source at the GC.. The B, C, G, J and GR observations were made with high-resolution Ge detectors. (From Leventhal et al. 1989).

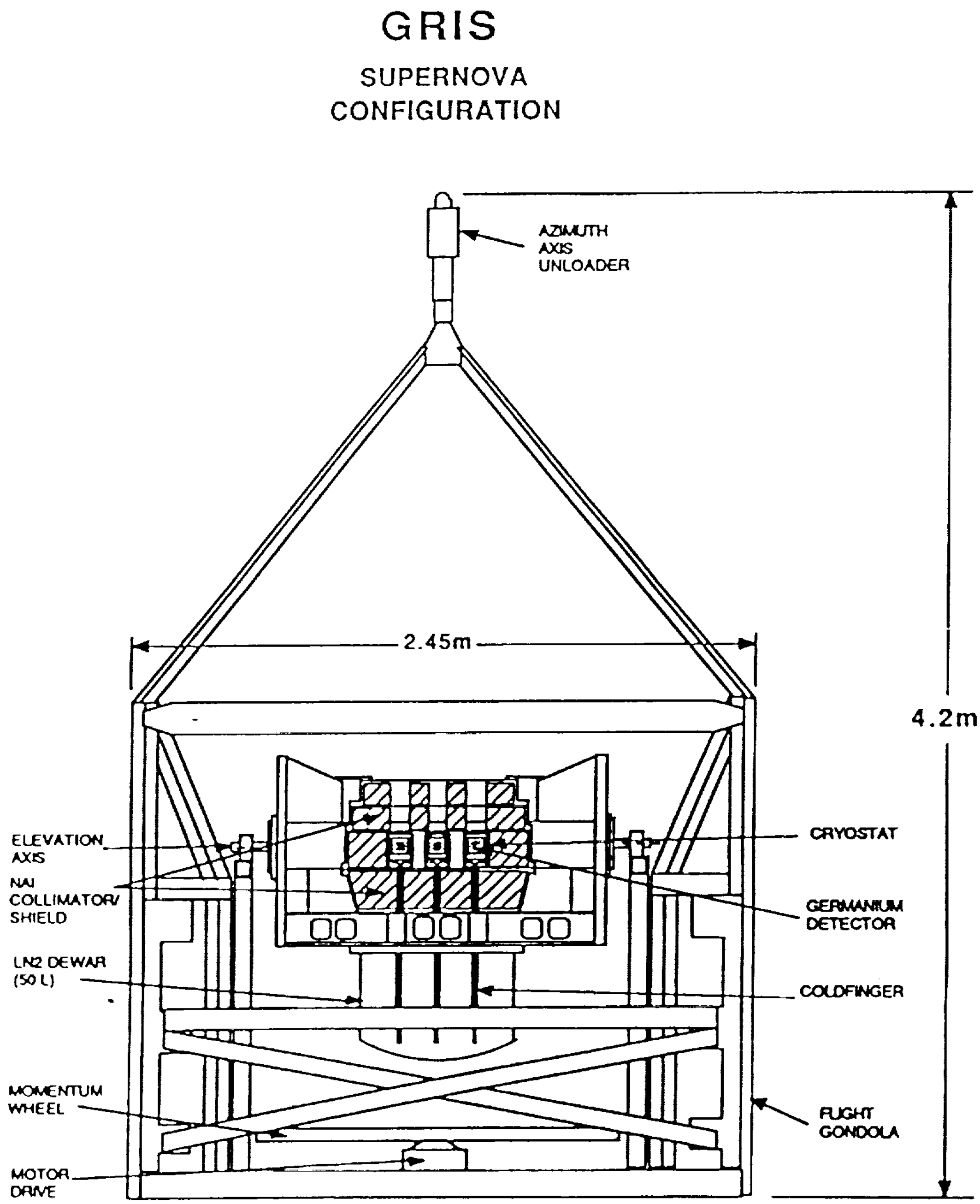

FIGURE 2

Cross-section of the GRIS payload as flown in May and October 1988.

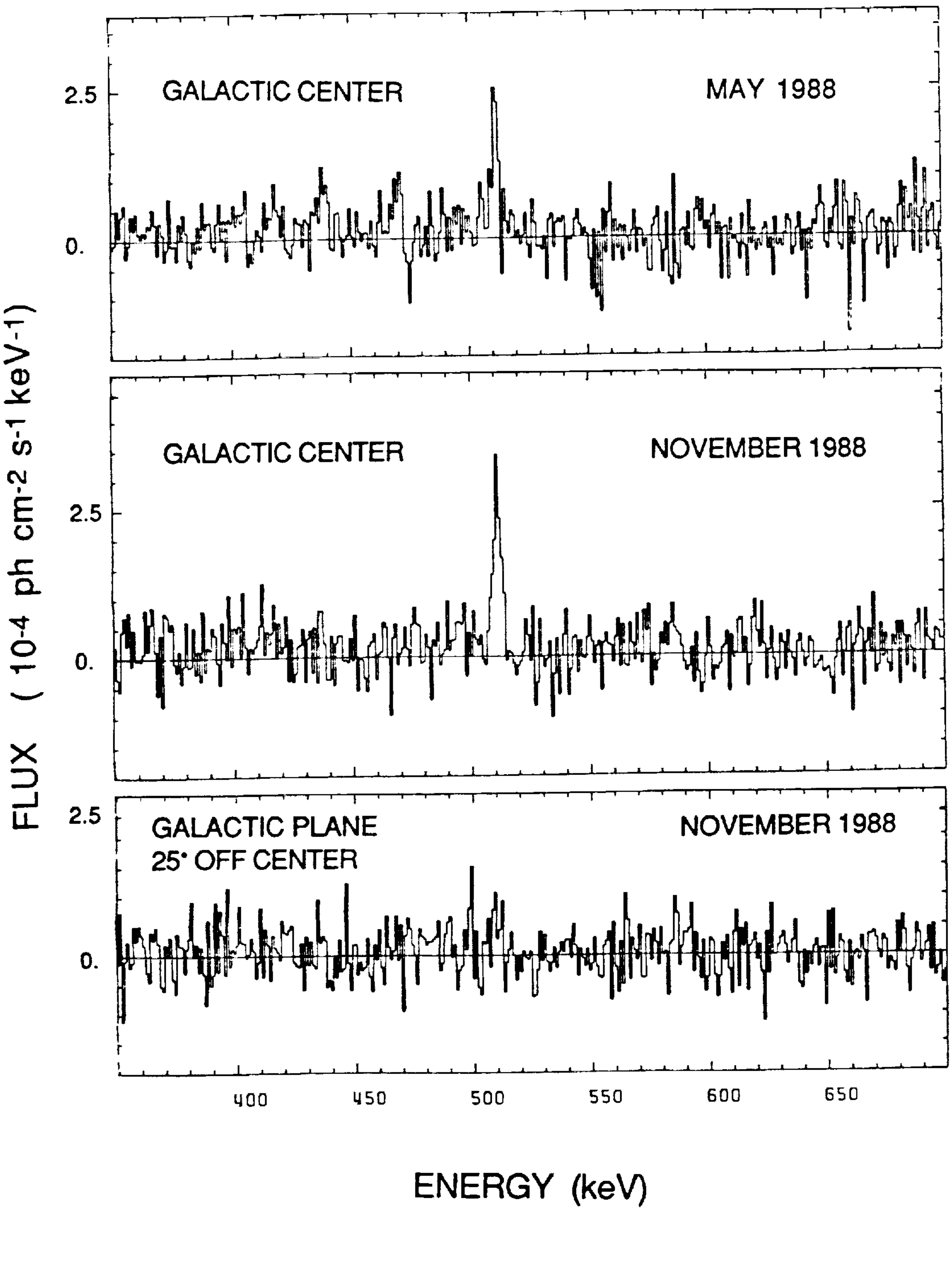

FIGURE 3
Spectra of the GC and GP near 511 keV measured by GRIS in May and October 1988. The data are background-subtracted fluxes that have been corrected for livetime, atmospheric attenuation and detector response to give source spectra.

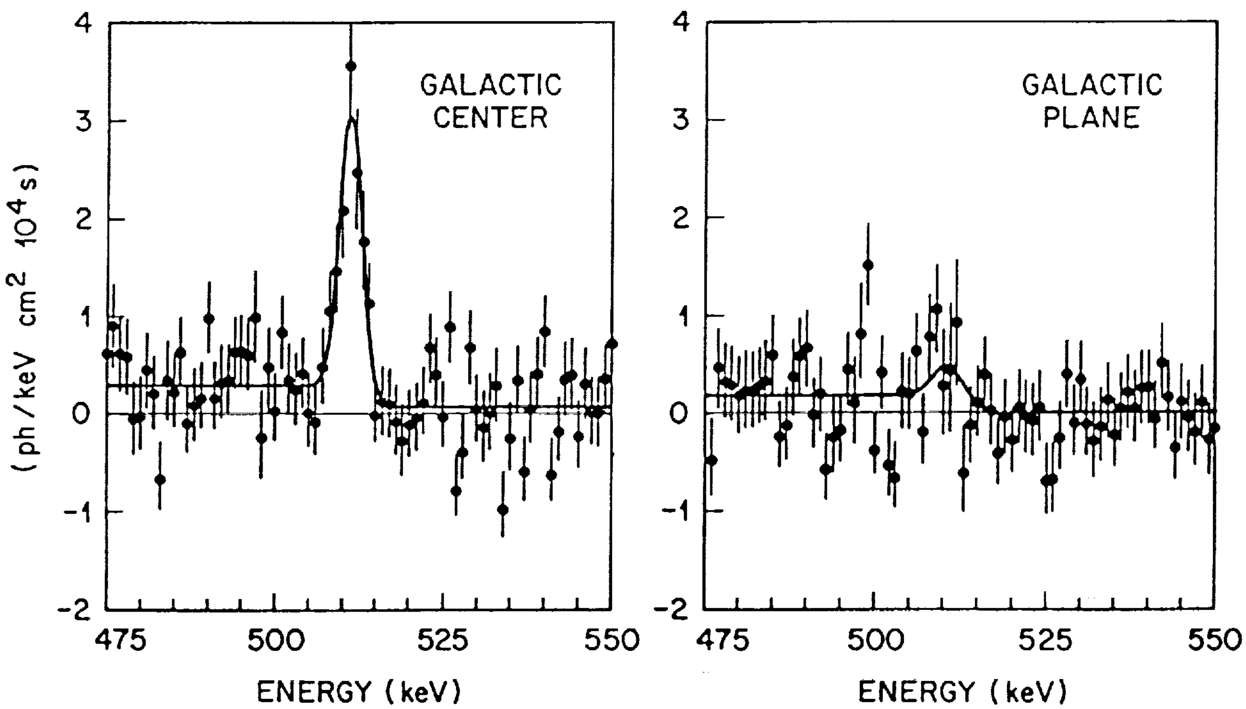

FIGURE 4

Source spectra of the GC and GP near 511 keV measured by GRIS in October 1988. The lines represent best fit models with a flat continuum, a step in the continuum at 511 keV and a Gaussian line. For the GP fit the line centroid is constrained to be at 511.0 keV.