OSSE Observations of Galactic 511 keV Positron Annihilation Radiation: Initial Phase 1 Results

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ABSTRACT

The Oriented Scintillation Spectrometer Experiment (OSSE) on the *Compton Gamma-Ray Observatory* (GRO) has performed numerous observations of the galactic plane and galactic center region to measure the distribution of galactic 511 keV positron annihilation radiation and to search for time variability of the emission; the initial 511 keV line fluxes for the observations performed during the first 18 months of the GRO mission are presented. The 511 keV line flux for a typical galactic center observation is $(2.5 \pm 0.3) \times 10^{-4}$ γ cm^{-2} s^{-1}, where the quoted uncertainty represents the 1 σ statistical uncertainty. No statistically significant time variability of the line flux has been observed; the 3 σ upper limit to daily variations from the mean is 3×10^{-4} γ cm^{-2} s^{-1}. The distribution of galactic 511 keV positron annihilation radiation implied by the OSSE observations is discussed and compared with observations by other instruments.

Subject Headings: gamma rays: observations – Galaxy: center – nucleosynthesis – ISM: general

1. INTRODUCTION

Observations of the galactic center region in the early 1970's provided the first evidence of galactic positron annihilation radiation (Johnson, Harnden & Haymes 1972; Johnson & Haymes 1973; Haymes *et al.* 1975); however, it was not until the late 1970's that the 511 keV line from positron annihilation was unambiguously identified and evidence for the detection of the positronium continuum reported (Leventhal, MacCallum & Stang 1978; Leventhal *et al.* 1980). Since that time, the galactic center region has been observed by numerous balloon and satellite-borne experiments (Riegler *et al.* 1981; Albernhe *et al.* 1981; Gardner *et al.* 1982; Paciesas *et al.* 1982; Leventhal *et al.* 1982; Leventhal *et al.* 1986; Share *et al.* 1988; Niel *et al.* 1990; Gehrels *et al.* 1991; Leventhal *et al.* 1993). These observations, however, have not been able to determine the location or distribution of the emission (see the recent reviews by Tueller 1993; Skibo, Ramaty & Leventhal 1992; Lingenfelter & Ramaty 1989). The situation has been further complicated by the possibility that the 511 keV annihilation line may vary in intensity by as much as $\sim 10^{-3}$ γ cm^{-2} s^{-1} (Riegler *et al.* 1981; Mahoney *et al.* 1988; Paciesas *et al.* 1982; Leventhal *et al.* 1982; Leventhal *et al.* 1986; Niel *et al.* 1990; Gehrels *et al.* 1991). The evidence for time variability of the 511 keV line flux has lead to the suggestion (Lingenfelter & Ramaty 1989) that the observed emission is composed of two separate sources: 1) a steady state diffuse galactic component, and 2) a time-variable point source near the galactic center. Possible sources of the diffuse galactic component include cosmic-ray interactions in the interstellar medium (Lingenfelter & Ramaty 1982), gamma-ray bursts (Lingenfelter & Hueter 1984), pulsars (Sturrock 1971), and β^+-decay products from radioactive nuclei (*e.g.*, ^{56}Co, ^{44}Sc, and ^{26}Al) produced by supernovae, novae, or Wolf-Rayet stars (Clayton 1973; Ramaty & Lingenfelter 1979; Signore & Vedrenne 1988; Woosley & Pinto 1988; Lingenfelter & Ramaty 1989). Photon-photon pair production in the vicinity of an accreting black hole has been suggested as a possible source of time variable annihilation emission (Lingenfelter & Ramaty 1982; Rees 1982; Ozernoy 1989; Ramaty *et al.* 1992). The Oriented Scintillation Spectrometer Experiment (OSSE) on NASA's *Compton Gamma-Ray Observatory* (GRO) satellite provides the unique ability to perform high-sensitivity observations of the galactic plane and galactic center region to map the distribution of positron annihilation radiation and to search for time variability of the emission. Here we report the initial results of the OSSE observations of the galactic plane and galactic center region which were performed during the first 18 months of the GRO mission. A discussion of the distribution of the 511 keV line emission will be presented separately (Purcell *et al.* 1993b).

2. OBSERVATIONS

The OSSE instrument (Johnson *et al.* 1993) consists of four separate, nearly identical detectors. The primary detecting element of each detector is a large area NaI(Tl)-CsI(Na) phoswich crystal which provides spectral information over the energy range 0.05 – 10 MeV. At 0.5 MeV, the nominal energy resolution is $\sim 9\%$ and the photopeak effective area is ~ 500 cm^2 for each detector. Tungsten slat collimators provide a field-of-view which is $3.8° \times 11.4°$ full-width at half-maximum (FWHM). Each detector has a separate elevation control system which provides independent positioning of the detectors about an axis parallel to the long axis of the collimators. During source observations, periodic background measurements are performed by offset-pointing the detectors from the target. Source and background observations are each typically 131 seconds in length, with the observations alternating between source and background measurements. See Johnson *et al.* (1993) for a detailed description of the OSSE instrument and its operation.

Observations with the GRO instruments are divided into viewing periods having a nominal duration of $\sim$ 2 weeks. During Phase 1 of the GRO mission (16 May 1991 — 17 November 1992), OSSE performed 17 separate observations of the galactic plane and galactic center region, providing a total of 28 weeks of data. A detailed description of these observations is given in Table 1. OSSE observations are primarily characterized by the target position and the collimator position angle. The collimator position angle represents the angle between the long axis of the collimator field-of-view and Galactic North, measured from North through East. The background offset angles represent the detector offset angles, relative to the target position, at which the background observations were performed. The on-source time represents the total accumulation time, in detector-seconds, for each of the source scan positions.

3. ANALYSIS AND RESULTS

The data were analyzed using the standard methods described in Johnson *et al.* (1993; see also Purcell *et al.* 1993a). Background estimation was performed for each source spectrum by fitting the nearest three or four background spectra, channel-by-channel, using a quadratic function in time. The background estimate was then subtracted from the source spectrum and the resulting difference spectra were summed separately for each detector and each source offset position. When summing the difference spectra, the propagation of the uncertainties included the correlation terms introduced by using the same offset-pointed background observation for multiple source spectra. The summed spectra were fitted by folding a photon model spectrum through the instrument response and comparing the resultant count spectrum with the observed spectrum. The parameters of the photon model were adjusted to minimize the χ^2 for the fit. The spectral fits were performed for all four detectors simultaneously using the same input photon spectrum. The errors represent the estimated 1 σ statistical uncertainty.

The spectrum for the July, 1991, observation of the galactic center is shown in Figure 1. This spectrum shows a strong line near 511 keV and evidence for a positronium-like continuum; there is no evidence for a backscatter feature near 170 keV. The fitted energy of the line is (507 ± 6) keV and the line width is consistent with the instrumental resolution. The spectral fit shown in Figure 1 was performed over the energy range 0.1 – 4.0 MeV and consisted of a single power-law, a photopeak line fixed in energy and width at 511 keV and 2.5 keV, respectively, and a positronium continuum component (Ore & Powell 1949). The spectral fit resulted in a 511 keV line flux of $(2.5 \pm 0.3) \times 10^{-4}$ γ cm^{-2} s^{-1} and a total positronium flux of $(9.2 \pm 0.7) \times 10^{-4}$ γ cm^{-2} s^{-1}. These fluxes correspond to a positronium fraction (Brown & Leventhal 1987) of (0.95 ± 0.04). Since the fitted positronium flux is dependent on the continuum model used in the fit, a detailed analysis of the positronium fraction will require a more rigorous treatment of the underlying continuum. The shape and intensity of the continuum, however, were not found to significantly affect the fitted intensity of the 511 keV line.

The fitted 511 keV line fluxes for all of the OSSE Phase 1 galactic plane and galactic center observations are given in Table 1. The galactic longitude distribution of the 511 keV line flux is found to be sharply peaked near the galactic center, consistent with the reported GRIS observations (Gehrels *et al.* 1991). The fluxes for the galactic center observations are found to be nearly independent of the collimator position angle, suggesting that a component of the emission is concentrated in the direction of the galactic center and is approximately azimuthally symmetric. Note that the OSSE fluxes represent differential measurements; the effect of the offset-pointed background observations must be included in any interpretation or model simulations of the OSSE data.

Time variability of the 511 keV line flux was investigated by separately summing the background-subtracted spectra for each of the galactic center observation intervals (see Table 1). These viewing period averaged spectra were fitted using the model described above. The resulting 511 keV line fluxes for observations within $\sim 1^\circ$ of the galactic center are shown in Figure 2; no significant variability of the 511 keV line flux is observed. After removing the best-fit diffuse component (see below), the 3 σ upper limit to variations from the mean is 1.5×10^{-4} γ cm^{-2} s^{-1}. A similar study was performed to search for daily variability; the 3 σ upper limit to daily variations from the mean is 3×10^{-4} γ cm^{-2} s^{-1}.

4. DISCUSSION

The OSSE data can be used to constrain the distribution of the 511 keV line emission and to place constraints on the variability of the emission. The data given in Table 1 are consistent with a two-component spatial distribution of the 511 keV line emission made up of: 1) a galactic bulge component which is concentrated in the direction of the galactic center and is approximately azimuthally symmetric, and 2) a galactic disk component producing significant emission at longitudes up to $\pm 20°$. It has been shown (Purcell *et al.* 1993a) that the OSSE data given in Table 1 can be well described by such a two-component diffuse distribution, though the data are also consistent with a constant point source with a flux of $\sim 1 - 3 \times 10^{-4}$ γ cm^{-2} s^{-1} located within a few degrees of the Galactic center and superimposed on a diffuse galactic distribution. A more detailed analysis of the distribution of the 511 keV line emission is in preparation (Purcell *et al.* 1993b). Figure 3 shows a comparison of the current OSSE two-component diffuse model with the results from other instruments, where the diffuse component for this model has been subtracted from the flux reported for each observation. This model is also consistent with the GRIS observations of the galactic center in April, 1992, (Leventhal *et al.* 1993) which were nearly simultaneous with one of the OSSE galactic center observations. The composite data shown in Figure 3 suggest a historical limit to a time-variable component of the 511 keV line flux of $\sim 5 \times 10^{-4}$ γ cm^{-2} s^{-1}. A similar comparison for the point + diffuse model would require time variability of up to $\sim 1.5 \times 10^{-3}$ γ cm^{-2} s^{-1}. As shown in Figures 2 and 3, the OSSE data are well-fit by the two-component diffuse model and do not require a time-variable component. For the galactic center observations, the 3 σ upper limit to variations in the 511 keV line flux from the mean is 1.5×10^{-4} γ cm^{-2} s^{-1} for weekly variability and 3×10^{-4} γ cm^{-2} s^{-1} for daily variability.

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Table 1

OSSE Phase I Galactic Center / Galactic Plane Observations

Viewing Period	Target Position[a]	Position Angle	Background Offset	Source Offset	511 keV Flux ($\times10^{-4}$ γ cm^{-2} s^{-1})	Observation Interval	On-Source Time ($\times10^5$ det-sec)
5	(0°, 0°)	–90°	±10°	3.0°	1.7 ± 0.5	12 – 24 July, 1991	1.0
				1.5°	1.9 ± 0.6	12 – 24 July, 1991	0.8
				0.0°	2.5 ± 0.3	12 – 24 July, 1991	3.5
				−1.5°	2.0 ± 0.5	12 – 24 July, 1991	0.8
				−3.0°	1.5 ± 0.5	12 – 24 July, 1991	0.9
7.5	(25°, 0°)	–90°	±10°	0.0°	-0.3 ± 0.4	15 – 22 Aug, 1991	2.3
9.0	(339°, 0°)	–90°	+4.3°/ −8.3°	0.0°	1.0 ± 0.4	5 – 12 Sept, 1991	2.1
10	(296°, 0°)	–84°	+4.5°/ −11.3°	0.0°	0.1 ± 0.2	19 Sept – 3 Oct, 1991	5.0
11	(0°, 0°)	66°	±12°	5.0°	-0.6 ± 1.4	7 – 10 Oct, 1991	0.1
				4.0°	2.0 ± 0.9	3 – 17 Oct, 1991	0.4
				3.0°	2.1 ± 1.2	7 – 12 Oct, 1991	0.2
				2.0°	2.3 ± 1.0	3 – 17 Oct, 1991	0.3
				1.0°	3.4 ± 1.1	7 – 12 Oct, 1991	0.3
				0.0°	2.5 ± 0.4	3 – 17 Oct, 1991	1.5
				−1.0°	2.7 ± 1.0	7 – 13 Oct, 1991	0.3
				−2.0°	3.5 ± 0.9	3 – 17 Oct, 1991	0.4
				−3.0°	1.7 ± 0.9	7 – 13 Oct, 1991	0.4
				−4.0°	-0.2 ± 1.9	3 – 17 Oct, 1991	0.5
				−5.0°	0.8 ± 1.4	7 – 10 Oct, 1991	0.2
13.0	(25°, 0°)	–90°	±10°	0.0°	0.6 ± 0.3	31 Oct – 7 Nov, 1991	4.4
13.5	(339°, 0°)	–90°	+4.3°/ −8.3°	0.0°	0.9 ± 0.3	7 – 14 Nov, 1991	2.7
14	(0°, 0°)	0°	±12°	4.0°	1.1 ± 1.4	14 – 25 Nov, 1991	0.1
				3.0°	2.1 ± 1.0	19 – 27 Nov, 1991	0.3
				2.0°	2.4 ± 1.6	14 – 25 Nov, 1991	0.1
				1.0°	2.5 ± 1.5	14 – 27 Nov, 1991	0.1
				0.0°	1.9 ± 0.7	14 – 28 Nov, 1991	0.6
				−1.0°	2.6 ± 0.9	14 – 26 Nov, 1991	0.4
				−2.0°	3.0 ± 1.5	14 – 18 Nov, 1991	0.1
				−4.0°	-0.3 ± 2.4	14 – 24 Nov, 1991	0.1
				−5.0°	0.1 ± 2.2	27 – 28 Nov, 1991	0.1
16	(0°, 0°)	90°	±10°	3.0°	1.3 ± 0.5	12 – 27 Dec, 1991	1.1
				1.5°	2.8 ± 0.5	12 – 27 Dec, 1991	1.2
				0.0°	2.3 ± 0.2	12 – 27 Dec, 1991	4.4
				−1.5°	2.4 ± 0.5	12 – 27 Dec, 1991	1.1
				−3.0°	0.4 ± 0.5	12 – 27 Dec, 1991	1.1
17[b]	(0°, 0°)	–32°	±6°→ ±12°	4.0°	0.6 ± 0.5	27 Dec, 1991 – 10 Jan, 1992	1.1
				2.0°	1.6 ± 0.5	27 Dec, 1991 – 10 Jan, 1992	1.0
				0.0°	2.5 ± 0.2	27 Dec, 1991 – 10 Jan, 1992	4.1
				−2.0°	1.8 ± 0.5	27 Dec, 1991 – 10 Jan, 1992	1.1
				−4.0°	1.1 ± 0.5	27 Dec, 1991 – 10 Jan, 1992	1.0
19[b]	(58°, 0°)	–90°	±10°	0.0°	-0.1 ± 0.2	23 Jan – 6 Feb, 1992	6.2
20[b]	(40°, 0°)	90°	±10°	2.3°	0.3 ± 0.3	6 – 20 Feb, 1992	2.4
				0.0°	0.5 ± 0.3	6 – 20 Feb, 1992	4.5
				−2.3°	0.3 ± 0.4	6 – 20 Feb, 1992	2.2
21[c]	(0°, 0°)	–96°	±10°	0.0°	2.6 ± 0.3	20 Feb – 5 Mar, 1992	4.4
24.0[b]	(0°, 0°)	96°	±10°	4.8°	0.5 ± 0.8	2 – 9 Apr, 1992	0.4
				0.0°	2.3 ± 0.5	2 – 9 Apr, 1992	0.9
				−4.8°	0.8 ± 0.8	2 – 9 Apr, 1992	0.4
24.5[b]	(5°, 0°)	93°	±10°	4.5°	1.0 ± 0.8	9 – 16 Apr, 1992	0.4
				0.0°	2.3 ± 0.6	9 – 16 Apr, 1992	0.8
				−4.5°	-0.3 ± 0.8	9 – 16 Apr, 1992	0.4
25[b]	(0°, 0°)	96°	±10°	0.0°	2.7 ± 0.5	16 – 23 Apr, 1992	1.2
				−4.8°	0.1 ± 0.8	16 – 23 Apr, 1992	0.4
40	(0°, 0°)	74°	+0.0°/ −4.0°	4.0°	-0.3 ± 0.8	17 Sep – 8 Oct, 1992	0.4
			+6.0°/ −10.0°	2.0°	1.2 ± 0.6	17 Sep – 8 Oct, 1992	0.7
			+4.0°/ −8.0°	0.0°	1.2 ± 0.7	17 Sep – 8 Oct, 1992	0.5
			+6.0°/ −10.0°	−2.0°	2.3 ± 0.9	17 Sep – 8 Oct, 1992	0.8

NOTES:

[a] In Galactic (lII, bII) coordinates.
[b] Detector gain at twice nominal value.
[c] Only observed by detectors 3 and 4.

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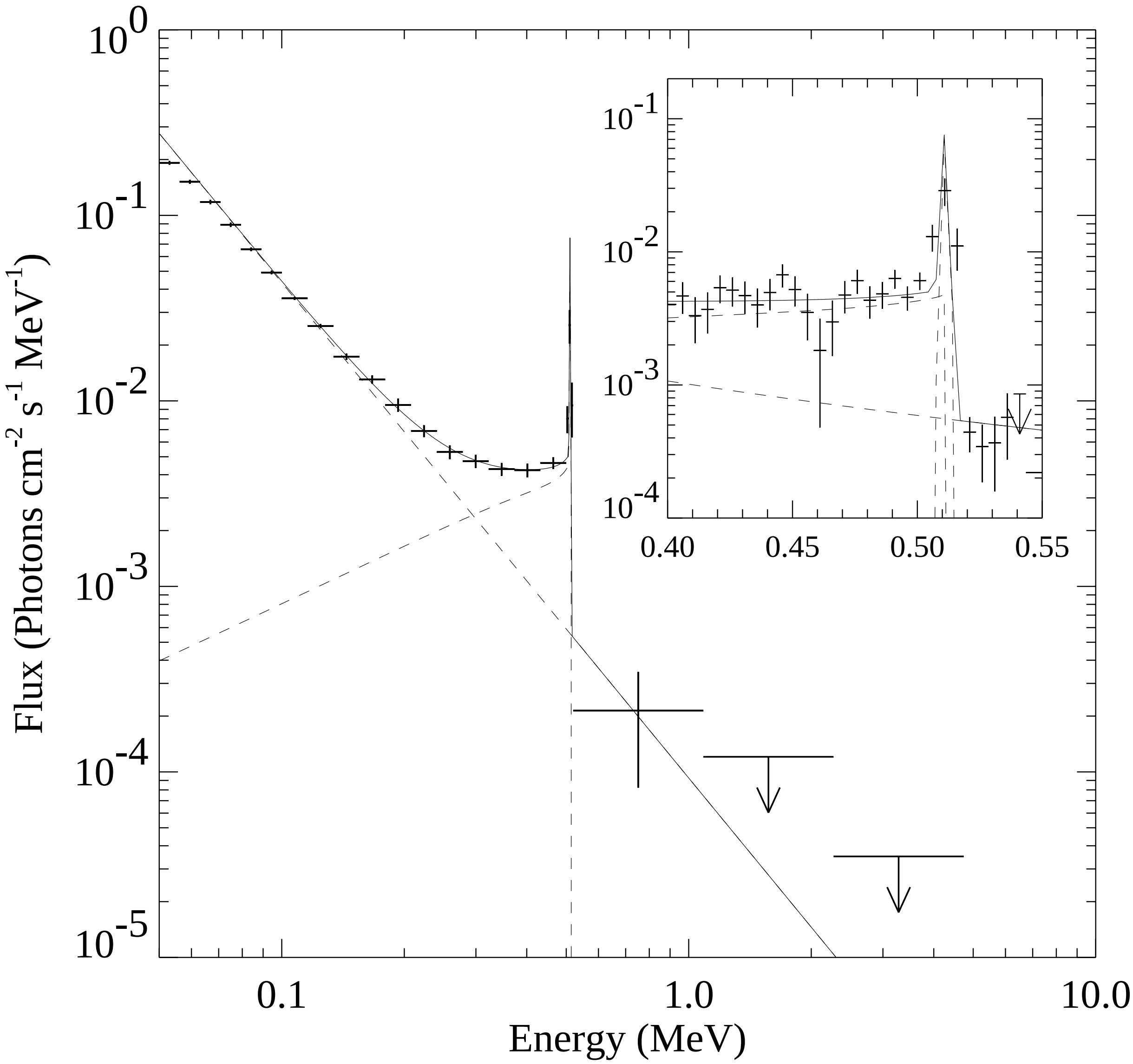
6. FIGURE CAPTIONS

Figure 1 – The OSSE galactic center spectrum from the July, 1991, observation. The spectrum represents the sum of all four detectors. The fitted function consists of a single power law, a photopeak line fixed in energy and width at 511 keV and 2.5 keV, respectively, and a positronium continuum component. The dashed lines indicate the contribution of each of these components.

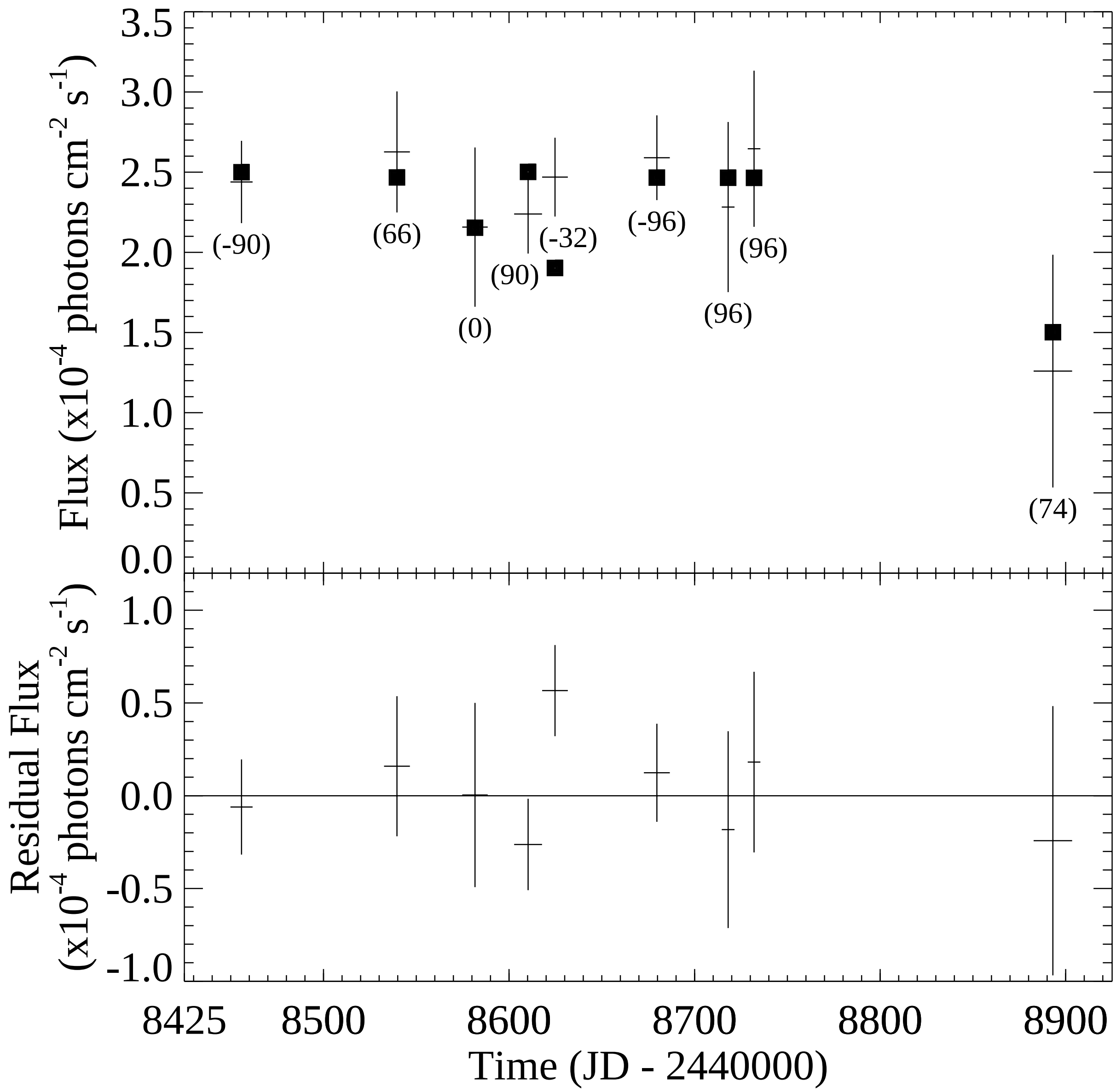
Figure 2 – The viewing period averaged 511 keV line flux for the OSSE galactic center observations. The numbers in parenthesis represent the OSSE collimator position angle for the associated observation interval. The squares indicate the best-fit two-component diffuse model flux.

Figure 3 – Historical summary of the 511 keV line flux from the galactic center region as observed by various balloon and satellite instruments, including the recent OSSE results. Note that the uncertainties displayed represent statistical uncertainties only. The diffuse contribution from the OSSE best-fit two-component model has been subtracted from the reported flux for each observation. References: SMM – (Share *et al.* 1990); GRIS – (Gehrels *et al.* 1991); Bell/Sandia – (Leventhal *et al.* 1978; Leventhal *et al.* 1980; Leventhal *et al.* 1982; Leventhal *et al.* 1986; Leventhal *et al.* 1993); FIGARO – (Neil *et al.* 1990); HEXAGONE – (Chapuis *et al.* 1991); CESR – (Albernhe *et al.* 1981); UNH – (Gardner *et al.* 1982); GSFC – (Paciesas *et al.* 1982).



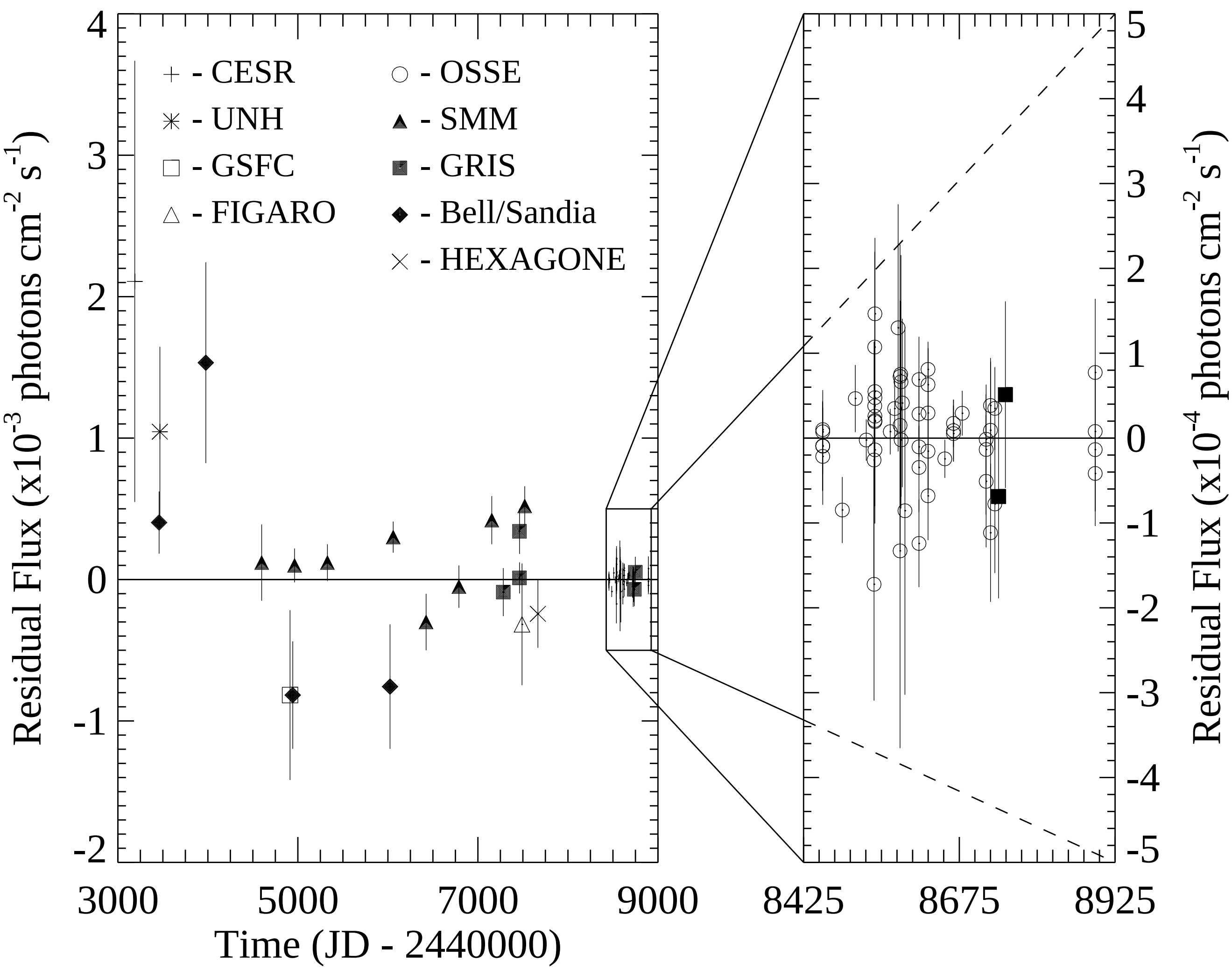
Flux (Photons cm-2 s-1 MeV-1)
Energy (MeV)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
0.1
1.0
10.0
0.40
0.45
0.50
0.55

Figure 1:



3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Flux (x10^{-4} photons cm^{-2} s^{-1})
(-90)
(66)
(0)
(90)
(-32)
(-96)
(96)
(96)
(74)
1.0
0.5
0.0
-0.5
-1.0
Residual Flux
(x10^{-4} photons cm^{-2} s^{-1})
8425
8500
8600
8700
8800
8900
Time (JD - 2440000)

Figure 2:



+ - CESR
✳ - UNH
□ - GSFC
△ - FIGARO
○ - OSSE
▲ - SMM
■ - GRIS
◆ - Bell/Sandia
× - HEXAGONE
Residual Flux (x10^{-3} photons cm^{-2} s^{-1})
Residual Flux (x10^{-4} photons cm^{-2} s^{-1})
Time (JD - 2440000)
3000
5000
7000
9000
8425
8675
8925

Figure 3: