OG 2.4.06

Galactic Positron Annihilation Observations with OSSE

J.D. Kurfess[1], P.A. Milne[2], M.D. Leising[3], D.D. Dixon[4] and R.L. Kinzer[1]

[1] *Naval Research Laboratory, Washington, DC 20375, USA*

[2] *NRC/NRL Resident Research Associate, Naval Research Laboratory, Washington, DC 20375, USA*

[3] *Department of Physics and Astronomy, Clemson University, Clemson, SC 29634-1911, USA*

[4] *Inst. for Geophysics and Planetary Sciences, University of California, Riverside CA 92521, USA*

Abstract

SMM/*GRS*, CGRO/*OSSE* and WIND/*TGRS* results indicate that the dominant 511 keV emission from the galactic center region is steady and of diffuse origin. The OSSE instrument on CGRO has provided the first maps of the 511 keV emission, and the discovery of a surprising excess at positive galactic latitudes above the center of the Galaxy (Purcell *et al*. 1997b). Most of the annihilation emission is in a 3-photon continuum below 500 keV. Although the continuum signal is stronger, with a positronium fraction near unity, the analysis is more complicated because of continuum contributions to the spectral fits from discrete sources and cosmic ray interactions with the. Kinzer *et al*. (1999b) report on 1-dimensional latitude and longitude distributions of the positronium continuum emission. Mapping the continuum emission is of importance in order to confirm the features in the 511 keV maps and to study the annihilation sites. We report on OSSE results with an expanded data set, which includes observations from CGRO cycles 7 and 8, inclusion of the positronium continuum emission, and additional pointed observations along the galactic plane not included in earlier analyses.

1 Introduction:

The OSSE instrument on NASA's COMPTON Observatory has provided the first information on the distribution of positron annihilation radiation in the galactic center region. The OSSE instrument has four identical detector systems, each with an independent, single-axis drive system and each with a 3.7° by 11.4° rectangular FoV (Johnson *et al*. 1993). Standard OSSE observations use 2-min alternating source and background measurements typically offset by ±4.5° in the narrow FoV direction. The initial galactic center and galactic plane observations were undertaken with the long axis of the collimator aligned with the plane of the Galaxy and with background observations offset in latitude by ± 10°. These larger background offsets are used to minimize the contributions of a few-degree-wide galactic plane emission in the background fields. For the initial galactic center studies, source observations were acquired at 0°, ± 1.5°, and ± 3° latitude to obtain good measurements of the galactic center and to search for any latitude extent to the emission. These initial observations yielded typical galactic center fluxes ~2.5 x 10^{-4} γ cm^{-2} s^{-1} (Purcell *et al*. 1993a). This low flux relative to the earlier wide FoV measurements, with reports of a total galactic center flux of 1-2 x 10^{-3} γ cm^{-2} s^{-1}, and the lack of any evidence for variability, lent strong support to the diffuse nature of the bulk of the emission. Furthermore, the emission was found to be distributed in latitude. Combining data from OSSE, SMM/*GRS* (Share *et al*. 1988) and GRIS (Gehrels *et al.* 1991), Purcell *et al.* (1993b) inferred a two-component model consisting of a central bulge with a total flux of (1.8 ± 0.2) x 10^{-3} γ cm^{-2} s^{-1} and a disk emission with a flux of (0.5 ± 0.2) x 10^{-3} γ cm^{-2} s^{-1}. However, these fluxes are quite model dependent.

A program of mapping the galactic center region with OSSE was then implemented. Purcell *et al.* (1997a) and Cheng *et al*. (1997) reported the initial 511 keV maps based on data from cycles 1-4 of the mission, and using maximum entropy and basis pursuit inversion techniques. The two techniques generated similar maps with three main features: (1) a central bulge ~5° in extent, (2) a disk component, and (3) evidence for excess emission at positive latitudes up to ~7°-10°.

Starting in *COMPTON* observing cycle 6, dedicated mapping observations were initiated. In these observations, the "standard" OSSE observational approach was replaced with "mapping" observations wherein each detector step-scanned through a ~25° region. Analyses of these data result in differential flux values vs. scan angle using orthogonal scans through galactic center region. Using a singular-value-decomposition (SVD) technique, Purcell *et al.* (1997b) reported on OSSE 511 keV distributions from data acquired through early 1997. They found the central bulge has a flux of ~3.5 x 10^{-4} γ cm^{-2} s^{-1}. The positive latitude feature has a flux of ~5-8 x 10^{-4} γ cm^{-2} s^{-1}, while the total emission in the disk is ~9-11 x 10^{-4} γ cm^{-2} s^{-1}. However, the latitude width and flux in the disk component is quite uncertain in their analysis. In their three-component model, any flux not contained in the central bulge or positive latitude enhancement is forced into the disk. If the disk emission is narrow, similar in width to the high-energy gamma-ray and diffuse X-ray disk emission, then the total emission in the OSSE maps may still fall short of the integrated flux measured by SMM. Additional data were clearly needed to further constrain the models.

2 Recent Results:

During *COMPTON* observing cycles 7 and 8, additional observations of the galactic center region, the galactic plane, and the positive latitude region were acquired. Furthermore, the data set used includes many additional observations, dedicated mostly to galactic X-ray sources with emission generally below several hundred keV (Milne *et al*. 1999). This results in a less uniform exposure of the region that may effect features in the maps. additional discrete source observations in the galactic center region have been added to the data set. Using this augmented data set, which approximately doubles the observing time relative to that used by Purcell *et al*. (1997b), enables revised 511 keV maps of the region. Two such maps, a Richardson-Lucy map and a SVD map, are shown in Figure 1. The main features remain the same, however: a central bulge, emission along the galactic plane (with features at locations of high exposure), and enhanced emission at positive latitude. The intensities of the components are consistent with those of Purcell *et al*. (1997b) when the total flux is normalized to SMM. However, as noted above, the intensity and distribution of the disk component are poorly determined and deep observations at longitudes > ± 20° are needed.

3 Models for the 511 keV Emission:

3.1 Central Bulge Component: The central bulge in the 511 keV maps is reminiscent of the nova distribution observed for other galaxies. Type Ia supernovae from such a white dwarf progenitor class could contribute much of this emission if positrons from ^{56}Co decay can escape the expanding debris due to weak or radial magnetic fields. Milne *et al*. (1999b) have recently shown that the late time (200-1000 days) light curves of several Type Ia supernovae appear to fall below the luminosity expected, if complete β^+ trapping is assumed, during this period when energy input from the ^{56}Co positrons dominates the overall energy budget. Chan and Lingenfelter (1993) studied such positron escape in detail. The data are consistent with ~5% ^{56}Co positron escape for an average Type Ia supernova. This mechanism could account for the most of the observed flux from the galactic center bulge (Milne *et al*. 1999b).

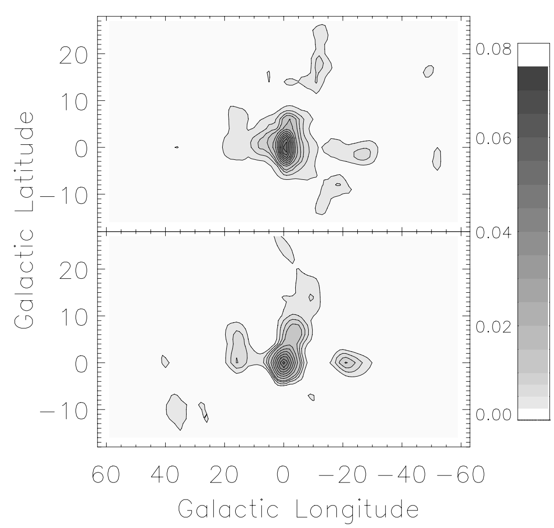

Figure 1. *Richardson-Lucy (top) and SVD (bottom) maps of the galactic 511 keV emission.*

3.2 Disk Component: A significant contribution to this emission are positrons associated with the decay of ^{26}Al ($\tau \sim 10^6$ yr.). COMPTEL has produced the first maps of ^{26}Al from the associated 1.809 MeV gamma ray emission (Diehl *et al.* 1995). The emission is confined to a rather narrow and clumpy disk, with a total intensity of ~3 x 10^{-4} γ cm^{-2} s^{-1} rad^{-1}. This should produce a disk contribution to the 511 keV emission with a central intensity of ~5 x 10^{-4} γ cm^{-2} s^{-1} rad^{-1}. Thus, positrons from the decay of ^{26}Al, produced by massive stars in the galactic plane, may account for most of the flux observed in the disk by OSSE, if the latitude distribution of this emission is ultimately found to be rather narrow. This appears to be the case based on latitude and longitude distributions of the 511 keV and positronium continuum fluxes (Kinzer *et al.* 1999b).

3.3 Positive Latitude Enhancement: The discovery of the positive latitude enhancement was a complete surprise, and its origin is a mystery. Dermer and Skibo (1997) have suggested that it could be due to a previous starburst epoch in the galactic center region. They suggest, for example, that one Type II supernovae per century during a starburst epoch one million years ago, and lasting 10^5 yr., could produce the requisite positrons. The pressure of the starburst bubble resulted in material breaking out toward the north galactic pole carrying the pair laden hot gas in which the positrons thermalize and annihilate. Observations of radio emission (Sofue *et al.* 1989) and thermal X-ray emission (Koyama *et al.* 1989) had previously suggested such activity. Recently, Duncan *et al.* (1998) have reported polarization observations that they interpret as evidence for a positron component to the ISM which exhibits a north-south asymmetry such as that inferred for the positron annihilation radiation.

4 Positronium Continuum Analysis:

Up to the present time, the positron annihilation mapping has been restricted to the 511 keV line. This was done because a determination of the 511 line flux in the OSSE spectra is immune to some of the systematic effects associated with continuum fits. The positron-electron annihilation process is dependent on the density and temperature in the annihilation region and can result in the emission of two photons, each with 511 keV energy, or in a three-photon continuum with a maximum energy at 511 keV. The positronium fraction, *F*, is defined as that fraction of the positrons that annihilate following formation of positronium, and is related to the line and continuum intensities by: $F = 2/[2.25(I_{511}/I_{ps}) + 1.5]$ where I_{511} and I_{ps} are the intensities of the line and continuum emissions respectively. However, with $F \sim 0.9$-1.0 (Purcell *et al.* 1997b, Harris *et al.* 1998), for every 511 keV gamma ray there are about 4 continuum photons emitted. For OSSE, the sensitivity for the positronium continuum emission should be about 2.5 times better than for the line emission. Thus, mapping analyses of the positronium continuum emission will be important. This will provide a check on the 511 keV map features and, in principle, provide information on the spatial distribution of the positronium fraction. The complications in fitting the positronium continuum emission are that spectral fits must properly include contributions from the diffuse galactic continuum gamma ray emission that results from cosmic ray interactions and from discrete X-ray sources (mostly confined to below 200 keV). The OSSE data set has been used to investigate the spectrum and distribution of the low-energy galactic continuum gamma-ray emission (Kinzer *et al.* 1999a).

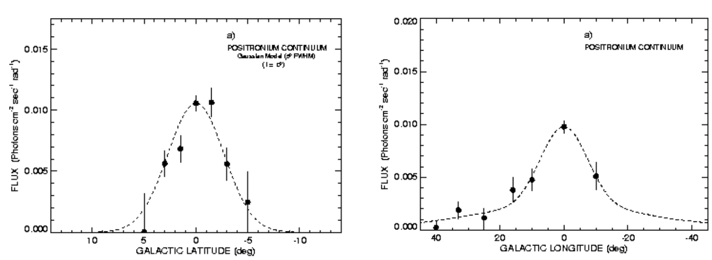

Figure 2. *The distribution of the positronium continuum emission in latitude (left) and longitude (right) from a subset of the OSSE data that primarily had the 11.4° collimator axis aligned with the galactic plane.*

Preliminary 1-dimensional distributions of the latitude and longitude distributions of the positronium continuum component were reported by Kinzer et al. (1996). With additional data and refinement to this analysis, recent 1-dimensional latitude and longitude distributions of the positronium continuum are shown in Figure 2 (Kinzer *et al*. 1999b).

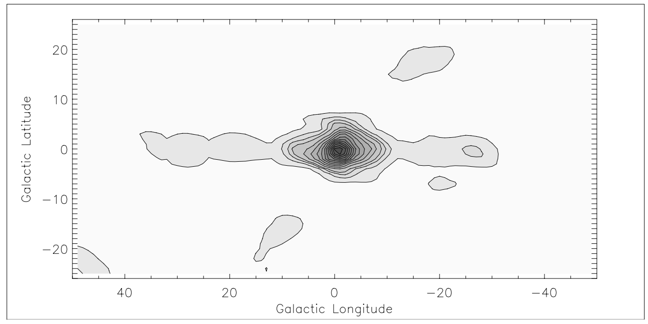

Figure 3. *Preliminary map of the total positron annihilation radiation from the galactic center region.*

5 Preliminary Mapping of the Total Positron Annihilation Radiation:

We are processing the ever-expanding OSSE data set to include mapping analysis of the 511 keV emission, the positronium continuum, and the total annihilation radiation. In this analysis, care must be taken to generate spectral fits to the composite spectra, including the positronium components, the underlying cosmic ray continuum, and the contributions from discrete sources. In general, the 511 keV results are robust, but this is not the case for the positronium continuum. The positronium continuum flux is more critically dependent on properly fitting the underlying cosmic ray continuum, understanding its spatial distribution, and the contribution of discrete sources at low energies.

Work continues on the re-processing and we are only about 1/4 of the way through the data set with optimal fits. (The fits used in the analysis of Purcell *et al*. (1997b) used only a power-law continuum and were adequate for the 511 keV intensities but are not adequate for the positronium continuum.). Figure 3 provides a preliminary map of the total annihilation emission base on this continuing work. When completed through the cycle 9 data, we will provide 511 keV, positronium continuum, and total positron annihilation radiation maps, as well as maps of the positronium fraction.

References

Chan, K., and Lingenfelter, R., 1993, ApJ **405**, 614
Cheng L.X., *et al*., 1997, ApJ **481**, 43
Dermer, C., and Skibo, J., 1997, ApJ **487**, L57
Diehl, R., *et al.*, 1995, A&A **298**, 445
Duncan, A.R., *et al*., 1998, MNRAS **299**, 942
Gehrels, N., *et al*., 1991 ApJ **375**, L13
Share, G.H., *et al*., 1988 ApJ **326** 717
Harris, M.J., *et al*., 1998 ApJ **501**, L55
Johnson, W.N., et al., 1993, ApJ Suppl. **86**, 693
Kinzer, R.L., *et al*., 1997, AIP Conf. Proc. **410**, 1193
Kinzer, R.L., *et al*., 1999a, ApJ **515** 215
Kinzer, R.L., *et al*., 1999b, ApJ to be submitted
Milne, P.A., *et al*., 1999a, to be published Proc. 3rd *INTEGRAL* Workshop
Milne, P.A., *et al*., 1999b, to be published in ApJ
Purcell, W.R. *et al*., 1993a, ApJ **413**, L85
Purcell, W.R. et al., 1993b AIP **280** 107
Purcell, W.R. *et al*., 1997a Proc. 2nd *INTEGRAL* Workshop, p.67
Purcell, W.R., *et al*., 1997b, ApJ **491**, 725
Sofue,Y., *et al*., 1989, ApJ **341**, 568