

# GAMMA-RAY EMISSION FROM THE INNER GALACTIC RIDGE

R.L. Kinzer<sup>1</sup>, W. R. Purcell<sup>2</sup>, J.D. Kurfess<sup>1</sup>

## ABSTRACT

An improved measurement of the composite 0.05 to 10 MeV gamma-ray spectra as a function of longitude from the inner galactic ridge has been made using the Oriented Scintillation Spectrometer Experiment (OSSE) on the Compton Gamma Ray Observatory. The continuum appears to be a composite of 3 independent components. A strong positron annihilation contribution is observed toward the center with an intensity which decreases rapidly with distance from the center (FWHM  $\sim 12^\circ$ ). A second contribution is a soft low-energy component with a broad longitude distribution and spectra well-approximated by an exponentially absorbed power-law. The third is a hard component with an approximately longitude-independent power-law spectral shape (photon index  $\sim -1.75$ ) from  $\sim 200$  keV to 10 MeV. When positron annihilation radiation is subtracted, this is the dominant feature above 0.2 MeV at all observed longitudes. For an assumed  $5^\circ$  FWHM latitude width at the center, the spectrum and intensity of this component agrees with extrapolations of measurements above 30 MeV using a cosmic-ray interaction model. When account is taken of bright source contributions, both these continuum components' distributions are consistent with the galactic CO longitude distribution along the plane. These results, in conjunction with previous measurements, provide new information for determining the galactic cosmic-ray electron spectrum down to the MeV region.

*Subject headings:* galaxies: individual (Milky Way) — gamma rays: spectra

## 1. INTRODUCTION

The center of the Galaxy has been studied as a gamma-ray source since the early 1970's. Until recently, gamma-ray detectors in the energy range below 50 MeV had either broad fields of view or inadequate sensitivity to resolve spectral and spatial characteristics of the emission. The large detectors with small point-spread functions required to understand the characteristics of radiation from this region were launched on the Compton Gamma Ray Observatory (*CGRO*) in 1991. Results from the *CGRO* instruments are now in hand to better understand this interesting gamma-ray "source".

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# Report Documentation Page

Form Approved  
OMB No. 0704-0188

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1. REPORT DATE <b>1997</b>		2. REPORT TYPE		3. DATES COVERED <b>00-00-1997 to 00-00-1997</b>	
4. TITLE AND SUBTITLE <b>Gamma-Ray Emission from the Inner Galactic Ridge</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Naval Research Laboratory, E.O. Hulburt Center for Space Research, 4555 Overlook Avenue, SW, Washington, DC, 20375</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES <b>29</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

The inner galactic disk emits gamma radiation with spectra made up of a number of distinct components. Understanding the spectral characteristics and spatial distribution of these components in the 50 keV to 10 MeV range provides information about nucleosynthesis in the Galaxy, about the cosmic ray electron spectrum, and about the interstellar medium and magnetic fields in which the cosmic rays propagate. Much of the observed gamma-ray emission below 10 MeV appears to be distributed over a narrow ridge along the galactic plane. Prior to the launch of *CGRO* the spectral shape and distribution below 30 MeV were not well understood. A summary of the gamma-ray data available prior to the launch of the *CGRO* indicated the need for more precise measurements (Gehrels & Tueller 1993). With results from instruments on *CGRO*, our understanding of the gamma-ray galaxy has dramatically improved.

The principal components of the central galactic ridge spectrum in the 0.05 to 10 MeV range are: a variable soft low energy component, important below  $\sim 300$  keV, known to contain strong contributions from discrete sources (e.g. Purcell et al. 1996, Gehrels & Tueller 1993, Peterson et al. 1990); a positronium annihilation continuum (e.g. Leventhal et al. 1978, Riegler et al. 1985, Harris et al. 1990, Gehrels et al. 1991, Slassi et al. 1991, Smith et al. 1993, Mahoney et al. 1993, Kinzer et al. 1996, Kinzer, Purcell, & Kurfess 1997); a 511 keV positron annihilation line (e.g. Johnson, Harnden & Haymes 1972, Leventhal et al. 1978, Riegler et al. 1981; Share et al. 1988; Gehrels et al. 1991, Slassi et al. 1991, Purcell et al. 1993, 1996; Kinzer et al. 1996, Kinzer, Purcell, & Kurfess 1997); a 1.809 MeV  $^{26}\text{Al}$  line (e.g. Mahoney et al. 1984, Share et al. 1985, Diehl et al. 1995, Teegarden et al. 1991); and a component resulting from cosmic-rays interacting with the interstellar medium (e.g. Harris et al. 1990, Bloemen et al. 1994, Strong et al. 1994, 1996). The soft low-energy component has a variable discrete-source contribution concentrated toward the center, but has an underlying stable component with a latitude width of about  $5^\circ$  FWHM (full width at half maximum) (Purcell et al. 1996). The galactic positron annihilation line and continuum components appear to come principally from a bulge about the center of about  $5^\circ$  FWHM in galactic latitude by  $12^\circ$  FWHM in longitude, with an additional ridge-like disk component distributed over the central radian (Purcell et al. 1994, Kinzer et al. 1996, Kinzer, Purcell, & Kurfess 1997). Note that there appears to be a broadly distributed positron annihilation flux underlying these narrow components to which OSSE is insensitive in a single observation due to its differential mode of background subtraction (e.g. Purcell et al. 1997). The narrow 1.809 MeV  $^{26}\text{Al}$  line follows a broad galactic-ridge longitude distribution (e.g. Diehl et al. 1995). The hard underlying continuum is principally from a narrow ridge along the plane with an  $\sim 80^\circ$  wide, roughly flat, maximum in longitude about the center at energies above 30 MeV (e.g. Hunter et al. 1997; Mayer-Hasselwander et al. 1982; Hartman et al. 1979). The low-energy part of this cosmic-ray induced component is thought to result principally from cosmic-ray electron bremsstrahlung and inverse Compton electron scattering on interstellar photons (e.g. Skibo, 1993; Strong et al. 1996), and may have a different distribution from the nucleon-interaction component dominant above  $\sim 70$  MeV (e.g. Bloemen et al. 1994, Strong et al. 1996). Because it is not possible to directly measure the cosmic-ray electron spectrum below  $\sim 1$  GeV, the gamma ray spectra provide one of the best means to determine the galactic electron spectrum at lower

energies.

The multi-component nature of the 0.05 to 10 MeV galactic plane spectrum presents a challenging observational problem. Because each of the components may follow a different latitude and longitude distribution, it is important for observations to be sensitive to intensity changes over a few degrees while resolving the spectral details at each position. Time variability can be addressed with multiple observations in the same direction.

Because of the this radiation's diffuse nature and OSSE's small field of view, deep and optimally configured observations are required for significant OSSE detections of the plane between 0.5 and 10 MeV. Although OSSE has made numerous observations of the galactic center region since its launch in 1991, most of these observations were designed to study the 0.511 MeV positron annihilation line distribution (e.g. Purcell et al. 1993, 1996) and to measure discrete source contributions. Six of these observations were configured with the OSSE collimator axis directed toward the plane and aligned with the long axis of the collimator parallel to the plane at four well separated longitude directions within  $\sim 60^\circ$  of the galactic center. These are the basis of the current report on measurements of the multi-component diffuse gamma-ray spectrum along the inner galactic plane.

## 2. OBSERVATION AND DATA ANALYSIS

The OSSE instrument comprises four identical and independent phoswich spectrometers with a total area of 2620 cm<sup>2</sup> and an effective area of  $\sim 2000$  cm<sup>2</sup> at 511 keV (see Johnson et al. 1993 for an instrument description). The detectors are sensitive to gamma-rays between about 50 keV and 10 MeV and have resolutions of  $\sim 8.8\%$  at 0.511 MeV. Each detector has an aperture of  $\sim 3.8^\circ$  by  $11.4^\circ$  FWHM defined by a passive tungsten slat collimator, and can be independently oriented in the narrow-angle direction. The current observations were conducted and processed in the manner described by Johnson et al. (1993). Appropriate spectral models were fit to each spectrum over the 0.05 to 10 MeV range using a forward-folding technique to determine the best fit photon spectrum for a given observation using the OSSE response matrices (e.g. Purcell et al. 1997). Background fields at  $\pm 10^\circ$  were observed alternately with the source field on 2 minute time-scales. In these observations, the large opening angle (the trans-scan direction) was aligned with the plane to maximize the signal from the extended galactic ridge while obtaining offset background measurements which were not contaminated by the narrow plane emission.

The broad galactic longitude distribution along the plane presents unique problems for the OSSE off-set pointing detectors above  $\sim 1$  MeV. At these energies, the detectors' angular response function develops significant "wings" relative to its triangular geometric response at lower energies, so that contributions from the galactic plane source are significant out to large incident angles. Because the current OSSE analyses employ background fields separated by  $\pm 10^\circ$  in scan angle from the plane direction, effects of leakage from angles well outside the central field of view will,

to first order, be removed from the difference (background-subtracted) spectra. Accurate analyses of diffuse source observations with OSSE require response matrices which take detailed account of the response to photons from all angles in both the source and background fields. In the current analysis, a full treatment of these effects has been implemented. The OSSE response over the entire  $4\pi$  ster of photon incident directions was determined with extensive calibrations prior to launch using radioactive sources and accelerator-generated photon beams in conjunction with extensive Monte-Carlo simulations. The calibration and Monte-Carlo results were used to generate the OSSE response matrices for both the source and the background fields. These were then used to obtain the net response matrices for background-subtracted spectra measured by OSSE when viewing an extended distribution of radiation.

Measurements of the galactic plane continuum spectra use background offset angles over twice as large as the nominal 4.5 degrees used in standard OSSE observations. For this reason, measurements of the galactic plane spectrum must take into consideration a subtle systematic dependence of the observed count-rate spectra on the scan angle of the detector relative to the spacecraft (Kurfess et al. 1997). The possible importance of such an effect was understood prior to the construction of OSSE; the collimator design and standard offset-pointing strategies were developed to minimize its significance. Although this effect has indeed proven to be negligible for standard observations ( $\pm 4.5^\circ$  background offset angles), it has recently been discovered that the effect can become important at energies below 200 keV and above about 700 keV for observations of sources near the OSSE sensitivity limit if large background offset angles are used. This dependence has been studied and understood using the extensive set of OSSE observations of weak-source fields and sky-mapping observations from the first 5 years of the mission (Kurfess et al. 1997). For the offset angles of  $\pm 10^\circ$  used in the current galactic plane observations, these corrections become significant for energies above about  $\sim 700$  keV. Corrections for this systematic effect were applied in the analyses reported here.

OSSE observed the galactic plane at the center in two identically-configured two-week observing sequences in July and December 1991. In each source observation, the collimator axis was directed toward the galactic center and the detector collimators were aligned with the long axis parallel to the galactic plane. A similar pair of one-week observations were made with the collimator axis directed at  $25^\circ$  galactic longitude in August and November 1991. Single two-week observations of the plane at  $40^\circ$  and at  $58^\circ$  longitude were made in February 1992 and January 1992, respectively (see Table 1 for details of the observations). During the galactic center observations, an equal amount of time was spent with the collimators directed toward a range of source latitudes spanning the expected width of the plane in order to map the width of the plane; these individual observations were not sufficiently deep to be used in the current analyses.

It is necessary to assume a distribution for the galactic plane radiation in determining the response matrices needed to derive photon fluxes from the measurements. Because OSSE's collimator will accept only a fraction of the flux from any of the extended galactic plane components, the derived flux intensities for each component are dependent on the assumed

distribution. We have assumed a flat longitude distribution in unfolding the OSSE response. Only the unfolded flux from the positron-annihilation components' sharply-peaked bulge distributions (Kinzer et al. 1996, Kinzer, Purcell, & Kurfess 1997, Purcell et al. 1996) will be strongly affected by this assumption, as discussed in Kinzer, Purcell, & Kurfess (1997). The other continuum components follow broad longitude distributions (see below) so that corrections for their actual distribution shapes are not large. For a given component, the estimated spectral intensities for any assumed longitude distribution shape can be unfolded from those obtained using the assumed flat distribution. Although the plane appears as a narrow ridge of emission at x-ray and gamma-ray energies, its latitude width is not well understood. Above  $\sim 1$  GeV it has a measured width of  $\leq 3^\circ$  FWHM (Mayer-Hasselwander et al., 1982, Hunter et al. 1997). At energies between 35 and 50 MeV, EGRET found a width of  $\sim 5^\circ$  to  $\sim 6^\circ$  (Hunter et al. 1997). Measurements with COMPTEL between 1 and 30 MeV (Strong et al., 1996) also give strong evidence for such a broader plane in this range. The continuum components below  $\sim 600$  keV from the galactic center direction have been directly measured with OSSE to have a galactic latitude width of  $\sim 5.5^\circ$  FWHM (Purcell et al. 1996). In the current analyses, the measured count-rate spectra were unfolded for a range of assumed widths in order to compare with previous results at overlapping and higher energies.

### 3. EXPERIMENTAL RESULTS

Figs. 1 shows the measured photon spectra, along with the best-fit composite photon spectral models, for the observations of the galactic plane at  $0^\circ$ ,  $25^\circ$ ,  $40^\circ$ , and  $58^\circ$ . Spectra in these figures were obtained assuming a  $5^\circ$  FWHM Gaussian latitude distribution for the plane. These photon spectra were derived from the measured count-rate spectra using standard forward-folding techniques to unfold the detector response using plausible models for the spectral components. In this method, the spectra were fitted by folding a photon model spectrum through the instrument response and comparing the resultant count spectrum with the observed spectrum. The photon model parameters were adjusted to minimize the  $\chi^2$  for the fit. As indicated in the figures and discussed above, the spectra contain at least the four different components: a hard cosmic-ray induced component, a soft low-energy component which includes discrete-source contributions, a positron annihilation 511 keV line component, and a positronium annihilation continuum component. The 1.809 MeV line component from the decay of  $^{26}\text{Al}$  in the plane has an intensity below the  $3\sigma$  sensitivity level of a single 2-week OSSE observation, and is not modeled here. The spectral shape to assume for each of the observed components is well defined only for the positronium continuum and the positron annihilation line (Ore and Powell, 1949). Models for the cosmic-ray interaction continuum (e.g. Skibo 1993, Bertsch et al. 1993, Strong et al. 1996) provide acceptable fits to the high-energy galactic plane continuum between 30 MeV and one GeV as measured by EGRET, COS B, and SAS 2. The variable soft low-energy component shape is determined here by fitting plausible spectral models to each measured spectrum. Because a principal part of this component is likely produced by an ensemble of discrete sources of varying

spectral type and intensity, we have studied several models which could represent this component: a single power-law model; a thermal Comptonization model (e.g. Sunyaev & Titarchuk, 1980), an exponentially-absorbed power-law model, and a broken power-law model. Table 2 gives the the  $\chi^2$  fit probabilities for each model for each observation.

Although data from experiments prior to the *CGRO* were able to only roughly define the low-energy gamma-ray spectrum (e.g. Gehrels & Tueller 1993), the OSSE galactic center observations (Fig. 1a) are of sufficiently high statistical quality over the 50 keV to 10 MeV range to permit investigating the spectral model(s) which optimally represent the soft low-energy component, along with the other components. The shape of each of the three continuum components has a direct bearing on the shape of the other components, so that a satisfactory overall fit to the full spectrum is essential in defining any continuum component well.

A best fit to the OSSE galactic plane spectra from the center direction (Fig. 1a) was obtained using the high-energy continuum model of Skibo (1993) in combination with an exponentially-absorbed power-law model for the soft low-energy component and with positron annihilation and positronium annihilation models (fitting parameters and probabilities are given for the best-fit model for all observations in Table 3). An equivalently good fit is obtained if a power-law ( $\alpha \sim -1.75$ ) is used for the cosmic-ray induced component (Table 2); its best-fit shape is similar to the shape of the Skibo model over the 0.05 to 10 MeV range. This four-component model represents the spectra over the full 0.05 to 10 MeV range well ( $\chi^2$  per degree of freedom of 1.07 and 0.71, probabilities of 0.37 and 0.84, respectively, for the two observations). The unique spectral shapes of the positron annihilation components permit their contributions to be reliably separated from the other components. In the two galactic center spectra in Fig. 1a, the soft low-energy component fluxes differ by about a factor of  $\sim 1.7$ . Such strong variations in the flux below 200 keV is produced by one or more bright and highly variable sources near the center. Using simultaneous observations of the galactic center region by OSSE and the SIGMA imaging gamma-ray telescope (e.g. Paul et al. 1991), Purcell et al (1996) showed that the  $\leq 300$  keV spectrum measured toward the center, after correction for the discrete sources resolved by SIGMA, was roughly the same intensity and shape as that at  $25^\circ$  and  $339^\circ$  longitude (e.g. Fig. 1b). This suggested a residual soft low-energy component broadly distributed in galactic longitude.

A number of plausible models for the soft low-energy continuum component and for the hard high-energy continuum have been investigated in order to determine the optimum composite model to describe the ensemble of the observations.  $\chi^2$  fit probabilities for each model combination are given in Table 2 for each observation. As indicated in the table, and shown in Fig. 2 where spectra from the four longitudes are plotted together, the best fit model at the center also gives satisfactory fits to the  $25^\circ$ ,  $40^\circ$ , and  $58^\circ$  longitude observations (albeit with different fit parameters, and with only the cosmic ray component being significant at  $58^\circ$ ).

Fig. 1b shows the photon spectrum from the summed  $25^\circ$  latitude observations, and the fit of the composite model (solid line) used in Fig. 1a, together with its separate components. Fig. 1c shows a similar fit to the  $40^\circ$  longitude observations. The  $58^\circ$  longitude observation is shown

in Fig. 1d, where the best-fit model required only the cosmic-ray interaction component. A single power-law gave a similar result (Table 2). Fig. 2 shows the composite model fits and the data from Fig. 1 (for a galactic plane latitude width of  $5^\circ$ ) together for comparison. The fitted parameters of the composite best-fit model, along with the  $\chi^2$  fit probability, for each of the observations are given in Table 3.

The low-energy component can be seen (Fig. 1a) to vary significantly with time at the center. Purcell et al. (1996) have shown that most of the difference between the galactic-center low-energy continuum and that at  $25^\circ$  results from contributions by bright discrete sources.

In Fig. 2 it appears that the soft low-energy component, after allowance for the discrete-source contribution at the center in viewing period 5, decreases more rapidly with distance from the center than does the cosmic-ray induced continuum. However, this may be an illusion produced by the detectors' changing collimator opening angle with energy. Fig. 3a shows the longitude distribution of the soft low-energy component (100 keV intensity) along with the galactic CO distribution shown by the dashed line (Dame et al. 1987; Dame, 1995) as smoothed by the OSSE collimators at 100 keV (solid line). This smoothed CO distribution, which is normalized to the lowest intensity galactic center observation (where variable source intensities are low), fits the modelled soft component distribution reasonably well. The same comparison is shown in Fig. 3b for the best-fit cosmic-ray induced continuum, with the CO distribution smoothed by the collimator response at 2 MeV (solid line). The significant "wings" on the collimator response in longitude at these energies cause significant smoothing and spreading of the input CO longitude distribution profile, resulting in an expected spatial distribution in reasonable agreement with that observed. Thus, both continuum components are consistent with the same CO distribution, with the apparent differences resulting principally from the differing collimator responses at low and high energies.

As discussed above, the  $3.8^\circ$  FWHM OSSE collimator opening angle causes the detectors to be progressively less sensitive to the diffuse ridge source as the assumed width for the ridge increases. Fig. 4 shows this dependence in the derived intensity of the galactic ridge spectrum, where the amplitude at a fixed energy (2 MeV) is plotted as a function of the FWHM of an assumed Gaussian latitude distribution. In the spectral analyses reported here, a width of  $5^\circ$  has been assumed unless specified otherwise.

Additional insight to the overall distribution of low-energy gamma-rays from the galactic center direction comes from comparing the small field-of-view OSSE observations of the galactic plane toward the center with similar observations made with the very broad field-of-view GRS instrument on the Solar Maximum Mission satellite (Harris et al. 1990), as shown in Fig. 5. The average measurements of the two galactic-center observations (shown separately in Fig. 1a) is indicated in the figure by the filled circles ( $5^\circ$  FWHM width assumed), with the best-fit model and its separate components shown as in Fig. 1a. The spectral shape and the range of systematic errors of the SMM GRS measurement of the spectrum from the central radian of the galactic plane are given by the dotted lines. Although the spectral shapes found with the two instruments

above 0.5 MeV are similar, their magnitudes differ by a factor of 2 to 4 (the SMM systematic error range). As shown in Fig. 3b, the central maximum of the galactic ridge continuum component above 0.5 MeV is distributed with a broad maximum over a range of longitudes roughly the same as the  $\sim 130^\circ$  FWHM field of view of the SMM detector, so that about a factor of two difference in the reported "per-radian" fluxes in that energy range is likely to result from the different opening angles of the two instruments when observing this feature. Because OSSE's narrow ( $3.8^\circ$  FWHM) collimator was used to make a differential measurement relative to "background" fields at  $\pm 10^\circ$  from the plane, these measurements are insensitive to any underlying broad galactic-latitude component. Such components would be only weakly detected by OSSE but would be fully detected by SMM, possibly causing intensity differences like those seen. In the 300 to 500 keV region (where the positronium flux dominates the cosmic-ray and low-energy continuum components in both measurements), the narrow-field OSSE detector and the broad-field SMM detectors report similar "per-radian" intensities. The relative differences in the observed intensities of the greater than 500 keV cosmic-ray component and the 300 to 500 keV (positronium annihilation) fluxes measured by the two instruments is illustrative of the very different spatial distributions of the cosmic-ray interaction component and the positronium continuum component, which has a narrow maximum in longitude of  $\sim 12^\circ$  FWHM (Kinzer et al. 1996, Kinzer, Purcell, & Kurfess 1997). In the positronium case, the narrow ( $11.4^\circ$  FWHM) OSSE collimator measures a large fraction of central positronium continuum bulge (together with a relatively small "bite" of the more broadly distributed underlying CR continuum), with the result that the reported OSSE positronium continuum points represent the intensity "per radian" only near the center. On the other hand, the SMM detector averages emission from the entire plane in the galactic center region, so that the flux reported smooths the sharp bulge component over its large field of view and includes contributions from any broad components like those reported by Purcell et al. (1997). The fact that these two measurements report comparable intensities in the 300 to 500 keV region, where the positronium continuum dominates, suggests that there are significant contributions from such broadly distributed components, and that the SMM flux is actually dominated by the positronium flux from directions away from the narrow galactic center bulge component. Such solid-angle effects have been similarly complicating factors in the interpretation of previous measurements of the multi-component galactic center spectrum with detectors having broad fields of view (e.g. Johnson and Haymes 1973, Peterson et al. 1990, Leventhal et al. 1978, Riegler et al. 1981, Gardner et al. 1982, Share et al. 1988, Gehrels et al. 1991, Chapius et al. 1991, Purcell et al. 1993, Gehrels & Tueller 1993).

Fig. 6 displays the OSSE spectrum of the plane toward the center, unfolded using an assumed galactic plane latitude width of  $5^\circ$  FWHM, with the positron-annihilation components removed. This figure shows only the soft low-energy component and the cosmic-ray induced component, which have a similar longitude distribution (Fig. 3). Above 511 keV, the average of the two galactic-center observations are shown, but below that energy only VP 16 is shown because it has a much-decreased contribution from bright variable sources. Discrete-source contributions were further reduced in the analysis of Purcell et al. (1996), shown by the crosses, where contributions

of the 5 resolved discrete sources in the galactic center region were removed. Positron-annihilation contributions have also been subtracted from the observations of Purcell et al. (1996). The figure shows the best fit model to the OSSE data alone for the soft low-energy component (dashed line) and the cosmic-ray interaction continuum using the model of Skibo 1993 (solid line). Recent *CGRO* measurements by the COMPTEL instrument (Strong et al. 1994) and the EGRET instrument (Hunter et al. 1997) at overlapping and higher energies are shown for comparison along with earlier high energy measurements by SAS 2 (Hartman et al. 1979) and COS B (Mayer-Hasselwander et al. 1982). The model of Skibo (1993) as fit to the OSSE data alone (Fig. 1a) is shown over the full range (solid line). The good agreement of the model shape with the OSSE data, the COMPTEL data, and with the data between 30 MeV and 1 GeV gives confidence in the validity of the leaky-box model of Skibo (1993) between 0.5 MeV and about a GeV. The two parallel dotted lines give the fitted spectra inferred from the OSSE observations with an assumed  $7^\circ$  FWHM plane width (upper curve) and  $3^\circ$  width (lower curve) over the energy range where the width is uncertain. Below 600 keV the continuum latitude width has been measured with OSSE to be  $\sim 5.4^\circ$  FWHM (Purcell et al. 1996). The intensity range bounded by these curves is somewhat greater than the range of systematic experimental uncertainties ( $\sim \pm 15\%$ ) in the 1 to 10 MeV range resulting principally from the OSSE scan-angle dependent background correction analysis. At energies below  $\sim 700$  keV these systematic uncertainties are insignificant in the current analyses.

Fig. 7 is a spectral energy density plot of the discrete-source and positron-annihilation corrected OSSE continuum measurements, along with the other galactic plane continuum measurements, shown in Fig. 6. Also shown is a recent discrete-source-corrected hard X-ray measurement of the inner galactic ridge (between  $\sim 1$  and 17 keV) using the LAC detector on the *Ginga* satellite (Yamasaki et al. 1996, 1997). This X-ray component is thought to be principally of a diffuse origin. A smooth connection can be drawn between the  $\leq 11$  keV LAC data and the source-corrected OSSE data, suggesting that the two may be from a common origin. This plotting format clearly demonstrates the sharp spectral break of about 1 in spectral index of this residual diffuse galactic plane continuum at  $\sim 300$  keV,

The agreement between the Skibo model, as fit to the OSSE data alone assuming a  $5^\circ$  FWHM plane, and the high-energy data suggests a roughly  $5^\circ$  width for the plane below about 10 MeV. This, taken together with the measured width of  $\sim 5.5^\circ$  below 600 keV determined by direct measurement using independent OSSE data (Purcell et al. 1996), lends support to the validity of the assumed width of  $\sim 5^\circ$  FWHM for the full 0.05 to 10 MeV range. These results suggest that the high-energy diffuse spectrum, powered below 70 MeV principally by cosmic-ray electron bremsstrahlung and inverse Compton scattering (e.g. Skibo, 1993; Strong et al. 1996), may extend smoothly to the soft gamma-ray range, but with a latitude width broadened by about a factor of 2 from the GeV range where the radiation mechanism is predominantly neutral pion decay (e.g. Hunter et al. 1997, Mayer-Hasselwander et al. 1982). The closeness of the OSSE  $\sim 5^\circ$  width and the  $5^\circ$  to  $6^\circ$  width estimated from EGRET spectral measurements in  $4^\circ$  wide latitude bands for

energies of 30 to 50 MeV (Hunter et al. 1997) gives support to this result. Agreement between the COMPTEL measurements and the OSSE data in the region of overlap give support to the current interpretation of the high-energy continuum, although a  $7^\circ$  FWHM plane agrees better with the COMPTEL data.

#### 4. DISCUSSION

The OSSE, COMPTEL, and EGRET instruments on the *CGRO* have provided measurements which give an improved estimate of the galactic plane gamma-ray spectrum over the 50 keV to 50 GeV range. Within the 50 keV to 10 MeV OSSE observations, the galactic plane spectrum displays the presence of four or more independent components which follow at least two different spatial dependences. Each of these components provides insight to the nature of one or more components of the inner-galaxy interstellar medium.

Several groups have developed models for the galactic-plane continuum using the interaction of cosmic ray nucleons and electrons with the interstellar medium to explain the observed gamma-ray spectrum above  $\sim 30$  MeV (e.g. Bertsch et al. 1993; Strong et al. 1994, 1996; Skibo, 1993; Skibo & Ramaty 1993; Skibo et al. 1996). At these energies the dominant contributors are neutral pion decay from cosmic-ray-nucleon interactions and cosmic-ray electron bremsstrahlung and inverse Compton scattering. One of these models has been extended to lower energies to explain the 1 to 30 MeV observations of COMPTEL (e.g. Strong et al. 1996). As shown in Fig. 6, the full-range model of Skibo (1993) agrees well with the ensemble of measurements between  $\sim 300$  keV and  $\sim 1$  GeV measured by *CGRO* instruments. At the galactic center, the positron-annihilation and soft low-energy components are dominant below 0.511 MeV (Fig. 1a) so that the cosmic-ray induced continuum is masked at these energies. However, at  $25^\circ$ ,  $40^\circ$ , and  $58^\circ$ , where the positron-annihilation components become progressively less significant with angular separation from the center (Figs. 1b, 1c, and 1d), the OSSE data demonstrate that the approximate power-law nature of the electron bremsstrahlung and/or inverse Compton scattering portion of this component may extend down to 200 keV or lower. The same spectral shape, represented by either the Skibo (1993) model or by a simple power-law spectrum with index  $\sim -1.75$ , represents the cosmic-ray component above 200 to 500 keV in each of the OSSE observations at longitudes out to  $58^\circ$ . This observed constant spectral shape as a function of longitude for the cosmic-ray component is in good agreement with the recent EGRET results which found no evidence for spectral shape change over the inner galaxy for energies above 30 MeV (Hunter et al. 1997). These spatial and spectral consistencies suggest that this hard spectral component observed by OSSE between  $\sim 200$  keV and 10 MeV is indeed an extension of the spectrum observed by EGRET, COS-B, and SAS-2 above 30 MeV, and by COMPTEL between 1 and 30 MeV.

There is now observational support for a broadening of the galactic ridge latitude distribution at low gamma-ray energies. Above one GeV the EGRET measurements, with a narrow

point-spread function, give a width of  $3^\circ$  or less (Hunter et al. 1997), in agreement with the measurements from COS B (Mayer-Hasselwander, 1982). Samimi and Kinzer (1994) reported a width consistent with this over the 20 to 1000 MeV range using a detector with a  $1^\circ$  point spread function. At 30 to 50 MeV, EGRET observed a deconvolved width of  $5^\circ$  to  $6^\circ$ , but with an  $\sim 9^\circ$  FWHM point-spread function at these energies. COMPTEL observations of the plane over the 1 to 30 MeV range are also consistent with a distribution of this width (e.g. Bloemen et al., 1994; Strong et al., 1996). The current OSSE observation of a soft gamma-ray ridge which appears to be roughly twice as wide as that above a GeV and which is more peaked toward the center, roughly following the galactic CO distribution, suggests that the distribution and confinement of cosmic-ray electrons may differ from those of the nuclear component. Strong et al. (1996) suggested that contributions from inverse-Compton scattering of electrons on interstellar photons could explain the observed broadened component at these energies. This improved understanding of the latitude width together with the current spectrum between 50 keV and 50 GeV (e.g. Figs. 1, 6, and 7) should lead to significant improvements in our understanding of the cosmic-ray electron spectrum and its confinement in the galaxy.

The current observations provide new input to the debate as to whether the bright-source-corrected soft low-energy continuum from the galactic ridge (excluding the positronium continuum) is from one or two (or more) separate components. In the past, this component has generally been treated as a single soft component (e.g. Gehrels and Tueller 1993; Purcell et al. 1996, Yamasaki et al. 1997), considered to be either a superposition of discrete sources, or from truly diffuse emission. A model has been developed which explains the full observed spectrum as a continuation of the high-energy cosmic-ray induced continuum resulting from bremsstrahlung by an enhanced cosmic-ray electron spectrum at low energies (Skibo & Ramaty 1993, Skibo et al. 1996). In the current observations, the approximate removal of the positronium continuum component and a cosmic-ray induced component leaves a significant soft, low-energy component which is well represented by an exponentially-absorbed power-law spectrum (Figs. 1a, 1b, and 1c), and almost as well by a thermal Comptonization spectrum. Purcell et al. 1996 have shown that a significant portion of this component near the center is from resolved discrete sources (Figs. 6 and 7). Although there are almost certainly further contributions from a distribution of weaker sources, their contributions may represent a small part of the residual spectrum (e.g. Yamasaki et al. 1997). The residual soft component can be represented equally well by a diffuse component (e.g. Skibo & Ramaty, 1993). The general agreement between the longitude distribution of this soft component and the CO distribution (Fig. 3) indicates that it is correlated with the matter distribution in the galaxy, as is the underlying hard cosmic-ray induced component. A better understanding of the soft low-energy component will require further simultaneous and correlated observations with OSSE and imaging detectors and/or narrow field-of-view detectors having sensitivity at overlapping and lower energies (for example, the HEXTE and PCS instruments on the *XTE* satellite) to isolate the discrete source contributions.

As shown in Figs. 1a and 1b, the 0.511 MeV positron annihilation line and the positronium

continuum are a dominant presence near the galactic center, but are barely detectable at  $25^\circ$  longitude. Their presence in the fitted model provides no improvement in the fits at  $40^\circ$  and  $58^\circ$  (Figs. 1c and 1d). Kinzer et al. (1996) and Kinzer, Purcell, & Kurfess (1997) used a selected set of optimally configured galactic plane observations (including those used here) to show that, in longitude, the positronium continuum and 511 keV line components are sharply peaked toward the center ( $\sim 12^\circ$  FWHM), while Purcell et al. (1996, 1997) used a much larger set of observations to map the 511 keV line intensity in the galactic center region to obtain a somewhat narrower bulge distribution about the center. Although the 511 keV line can be accurately measured without fully understanding the underlying continuum, precise measurements of the positronium continuum, and thus of the positronium fraction, require accurate fits to the underlying continua. Measurements of the positronium fraction at the center and of the positron annihilation radiation distribution in the inner galactic ridge are reported separately (Kinzer et al. 1997, Kinzer, Purcell, & Kurfess 1997).

The current results provide significant improvements in our understanding of both the intensity and spectral distributions of the cosmic-ray induced and the soft low-energy gamma-ray continuum components from the galactic plane towards the center. Because OSSE is still operating at 100% of its original capability, it has the inherent capability to greatly improve the quality of this understanding at high energies by performing deeper (4 to 10 week) observations in a systematic program specifically designed to study the galactic plane continuum emissions, and at low energies by performing coordinated simultaneous observations with imaging or finely-collimated detectors.

We acknowledge helpful discussions with Mark Strickman, Neil Johnson, Jeff Skibo, Gregory Jung, Andrew Strong, and Stanley Hunter. This work was supported under NASA grant DPR S-10987C.

Dates	Viewing		Orientation <sup>b</sup>	Direction ( $l^{II}, b^{II}$ )
	Period	Live Time <sup>a</sup>		
1991 July 12-24	5	4.5	90°	(0°, 0°)
1991 December 12-27	16	5.5	90°	(0°, 0°)
1991 August 15-22	7	1.2	90°	(25°, 0°)
1991 October 31-November 7	13	5.1	90°	(25°, 0°)
1992 February 6-20	20	4.8	90°	(40°, 0°)
1992 January 23-February 6	19	7.2	90°	(58°, 0°)

Table 1: OSSE GALACTIC PLANE OBSERVATIONS

<sup>a</sup> Total live-times for background-subtracted and screened data in units of  $10^5$  seconds per single-detector on source.

<sup>b</sup> Galactic position angle (angle relative to galactic north) of the long direction of the collimator.

MODEL	OBSERVATION ( $l^{II}, b^{II}$ )					
	VP 5 (0°, 0°)	VP 16 (0°, 0°)	VP 5+16 (0°, 0°)	VP 7+13 (0°, 25°)	VP 20 (0°, 40°)	VP 19 (0°, 58°)
POS <sup>b</sup> +PLE <sup>c</sup> +CR <sup>d</sup>	0.37	0.84	0.35	0.065	0.24	
PLE+CR					0.32	0.29
POS+COM <sup>e</sup> +CR	0.26	0.66	0.11	0.046	0.23	
COM+CR					0.32	0.29
POS+PL <sup>f</sup> +CR	0.02	0.12	0.001	0.011	0.11	
PL+CR					0.16	0.34
POS+PLE+PL	0.31	0.94	0.33	0.057	0.16	
POS+COM+PL					0.048	0.20
POS+PL+PL	0.03	0.21	0.007	0.014	0.11	
POS+BPL <sup>g</sup>	0.03	0.16	0.12	0.02	0.13	
BPL					0.20	
POS+PL	0.02	0.01	$1.0 \times 10^{-5}$	0.015	0.06	
PL						0.40
CR						0.45

Table 2: CHI-SQUARED PROBABILITIES<sup>a</sup>OF MODEL FITS

<sup>a</sup> Probability that a greater chi-squared value would be found for intensities normally distributed about the local mean.

<sup>b</sup> Positronium continuum plus a 2.5 keV FWHM Gaussian 511 keV line.

<sup>c</sup> Exponentially cut-off power-law model:  $A(E/E_o)^{-\Gamma_1} e^{-(E-E_o)/E_c}$ .

<sup>d</sup> Cosmic-ray interaction model of Skibo (1993).

<sup>e</sup> Thermal Comptonization model of Sunyaev & Titarchuk (1980).

<sup>f</sup> Single power-law model:  $A(E/E_o)^{-\Gamma_2}$ .

<sup>g</sup> Double or broken power-law ( $E$  = energy in MeV,  $E_b$  = break energy):  $A(E/E_b)^{-\Gamma_1}$  for  $E < E_b$ ,  $A(E/E_b)^{-\Gamma_2}$  for  $E > E_b$ .

VP	OBS. ( $l^I, b^I$ )	$A_{exp}^c$	Model Parameter Values <sup>a</sup>					Prob. <sup>e</sup>
			$\Gamma_1$	$E_c$ or $kT^b$	$A_{CR}^c$	$A_{511}^d$	$A_{POS}^d$	
5	(0°, 0°)	0.433 ± 0.011	-1.96 ± 0.16	0.180 ± 0.060	4.95 ± 0.99	1.87 ± 0.28	10.21 ± 1.04	0.37
16	(0°, 0°)	0.257 ± 0.008	-1.39 ± 0.28	0.067 ± 0.012	5.62 ± 0.76	1.72 ± 0.21	10.54 ± 0.63	0.84
5 + 16	(0°, 0°)	0.335 ± 0.008	-1.84 ± 0.16	0.124 ± 0.028	5.25 ± 0.69	1.80 ± 0.19	10.50 ± 0.64	0.35
7 + 13	(25°, 0°)	0.146 ± 0.011	-1.66 ± 0.52	0.130 ± 0.091	3.75 ± 1.16	0.16 ± 0.26	1.26 ± 0.92	0.07
20	(40°, 0°)	0.061 ± 0.013	-1.96 ± 2.14	0.027 ± 0.021	3.69 ± 1.13	0.17 ± 0.28	0.00 ± 0.32	0.24
20	(40°, 0°)	0.061 ± 0.010	-0.00 ± 0.74	0.025 ± 0.017	3.75 ± 0.76			0.32
19	(58°, 0°)				1.59 ± 0.29			0.45

Table 3: BEST-FIT MODEL PARAMETER VALUES

<sup>a</sup> Model is combination of exponentially cut-off power-law model,  $A_{exp}(E/E_o)^{-\Gamma_1} e^{-(E-E_o)/E_c}$ , (where  $E_o = 0.1$  MeV), plus positronium continuum model (flux =  $A_{POS}$ ) plus narrow 511 keV annihilation line (flux =  $A_{511}$ ) plus cosmic-ray interaction model of Skibo 1993 (intensity =  $A_{cr}$  at 0.1 MeV).

<sup>b</sup> Units are MeV

<sup>c</sup> Collimator-smoothed amplitude at 0.1 MeV in units of  $10^{-2} \text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1} \text{rad}^{-1}$

<sup>d</sup> Collimator-smoothed integral flux in units of  $10^{-3} \text{cm}^{-2} \text{s}^{-1} \text{rad}^{-1}$

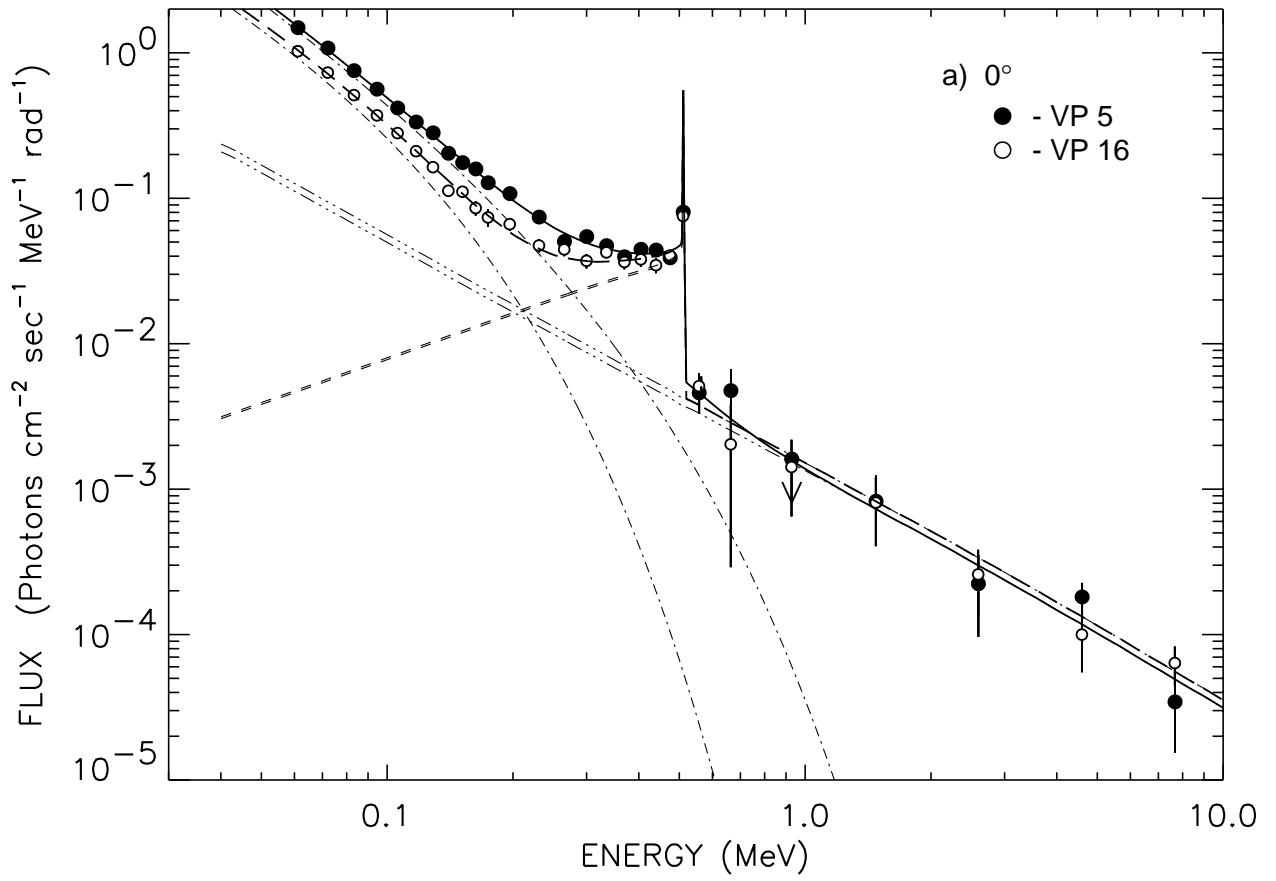
<sup>e</sup> Probability that a greater chi-squared value would be found for intensities normally distributed about the local mean.

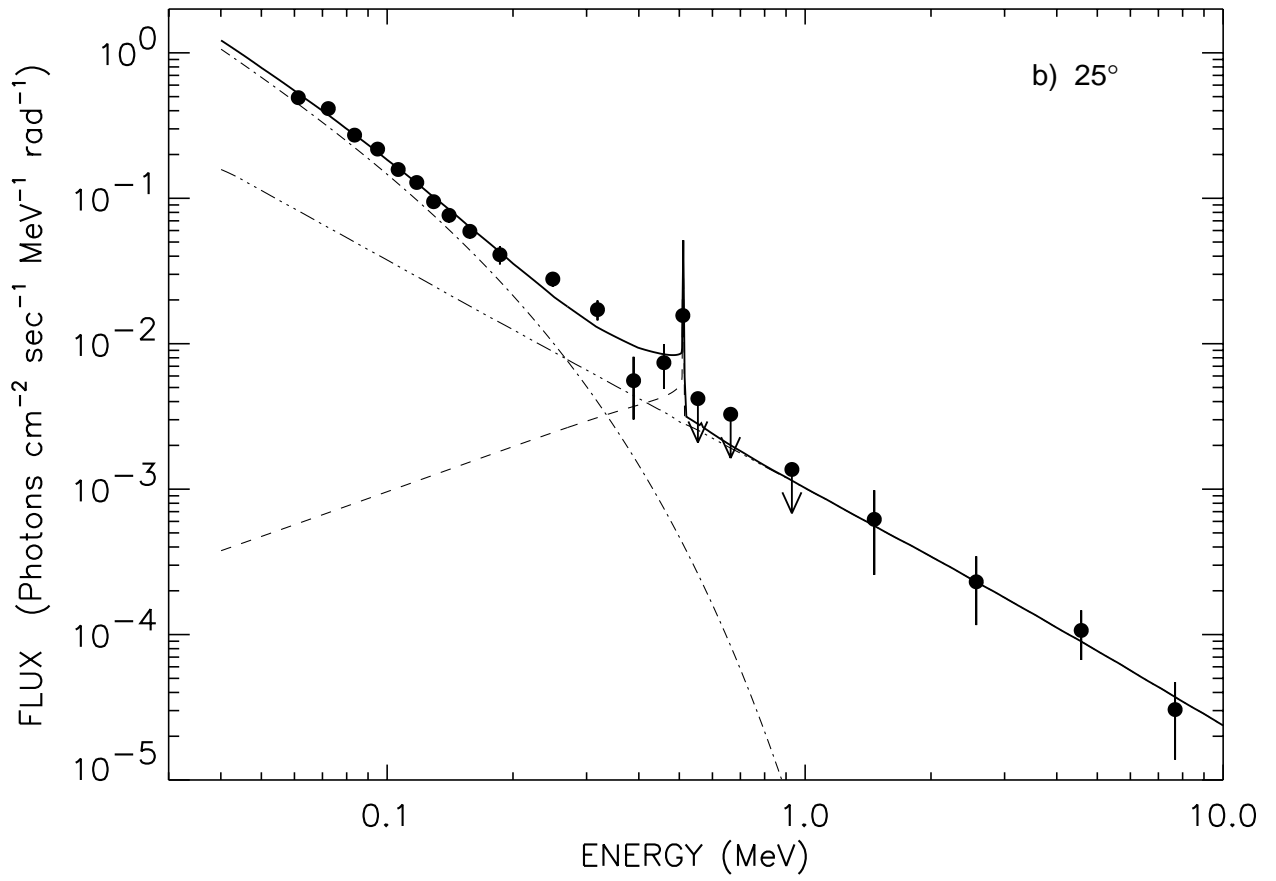
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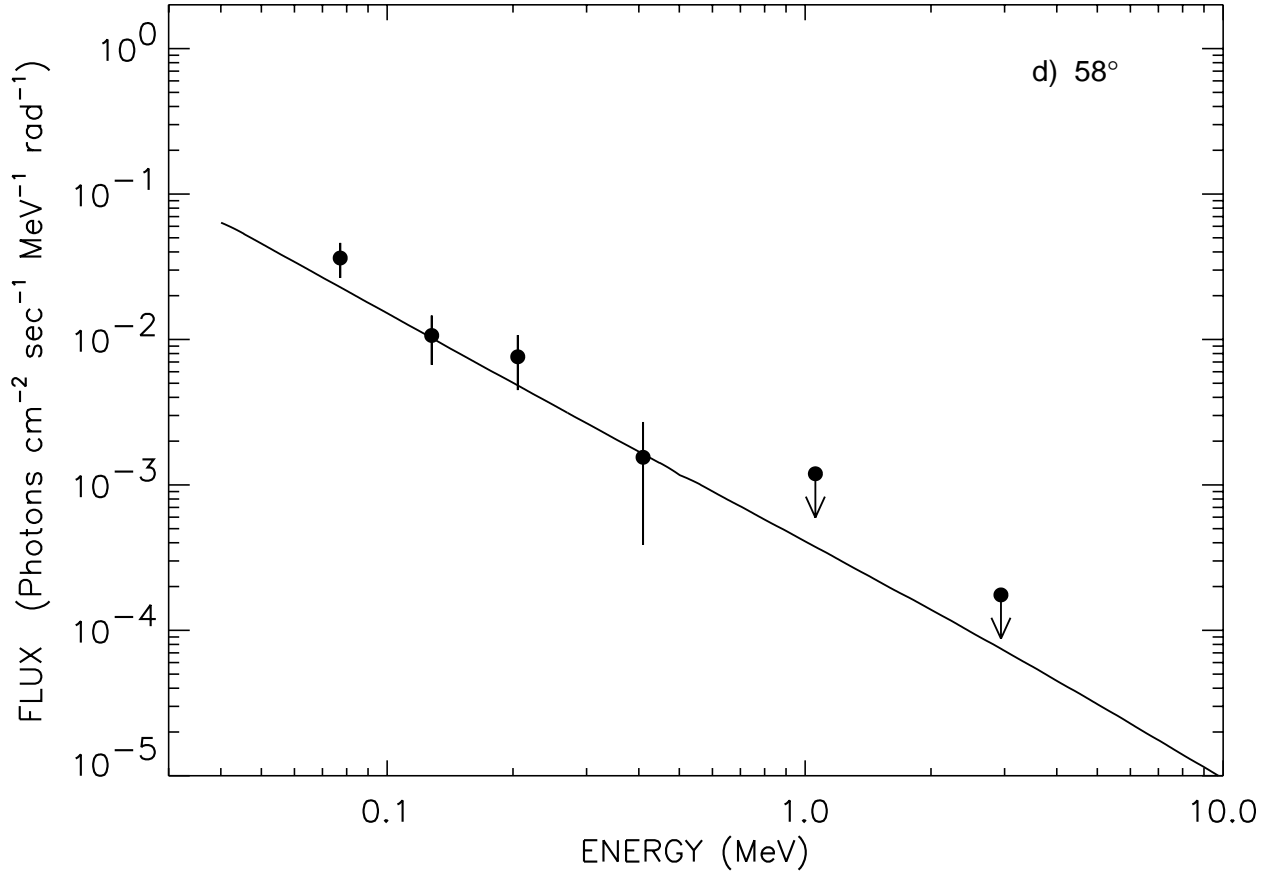


Fig. 1.— Spectra of 5 observations of the galactic plane for an assumed 5° FWHM galactic ridge distribution. Best-fit composite models are shown by the solid lines or by a long-dashed line. Model components are: dashed-dotted line - exponentially absorbed power-law component; dashed line - positronium continuum component and a 2.5 keV FWHM narrow line at 0.511 MeV; dashed-triple-dotted line - cosmic-ray interaction continuum model of Skibo (1993). Two results at 0° (VP 5 & VP 16), and one at 25° (VP 7 + 13), at 40°, and at 58° longitude are given in a), b), c), and d), respectively, with the best fit of the same model function for each spectrum.

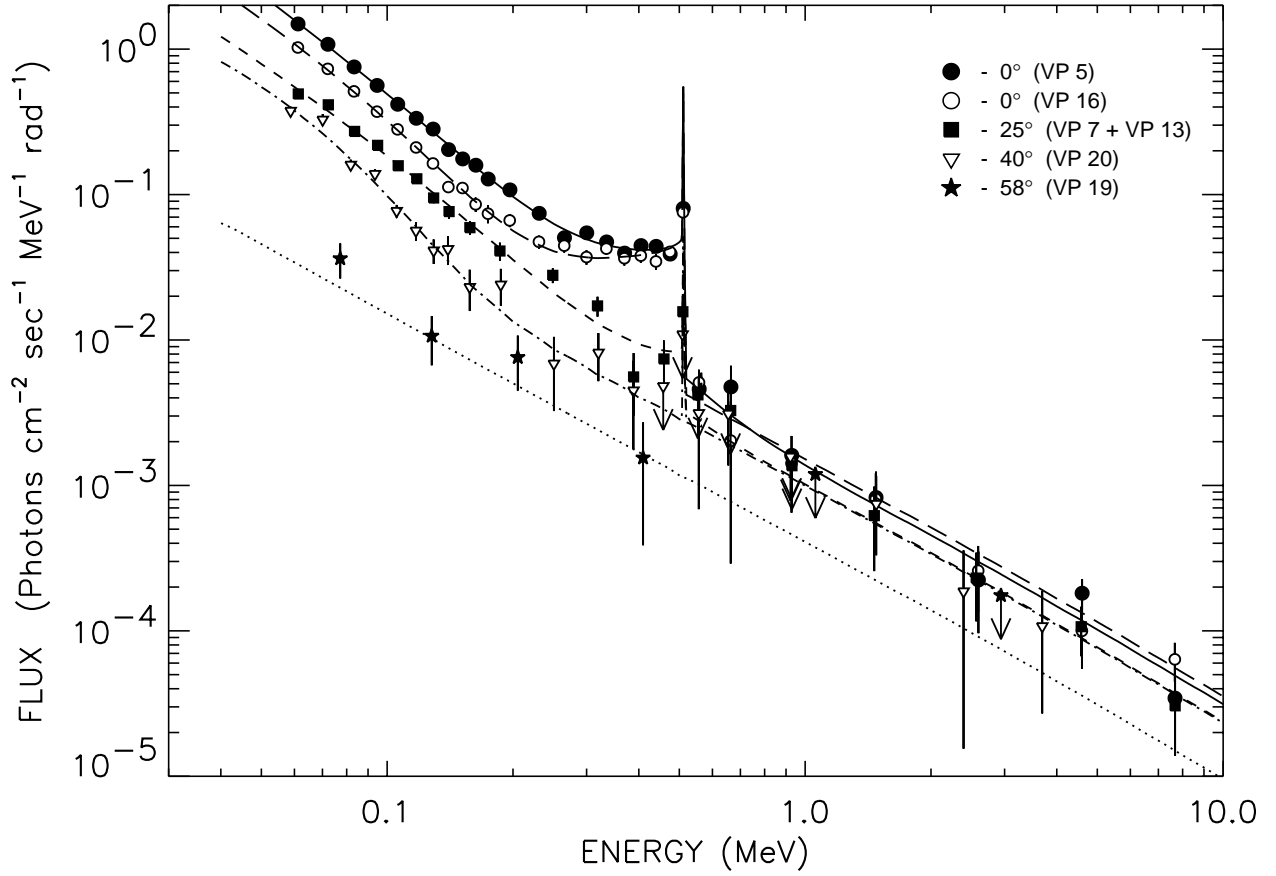
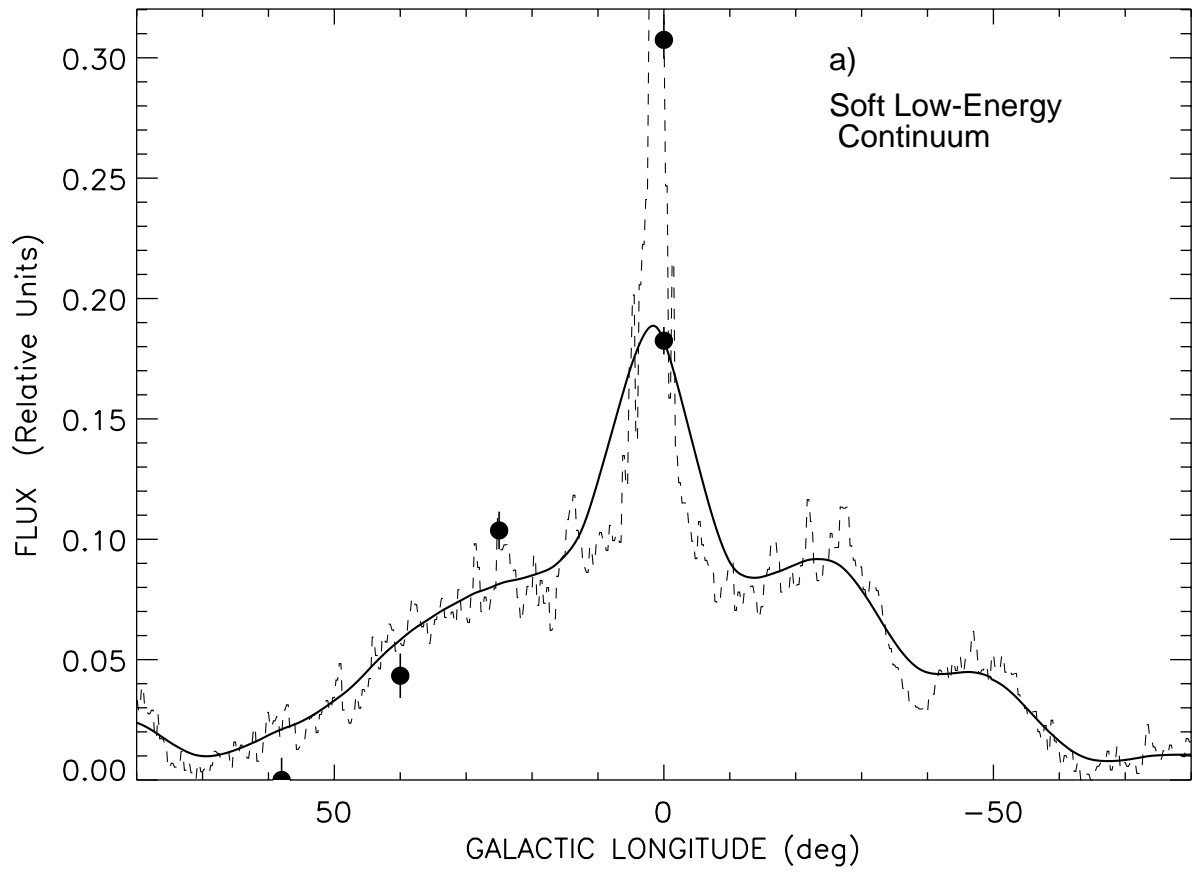


Fig. 2.— Observations and composite best fit models (as shown in Fig. 1) at 0° (filled circles, solid line for VP 5 and open circles, long-dashed line for VP 16), at 25° (filled squares, dashed line), at 40° (open triangles, dashed-dotted line), and 58° (filled stars, dotted line). At 58°, only the cosmic-ray interaction model of Skibo is used.



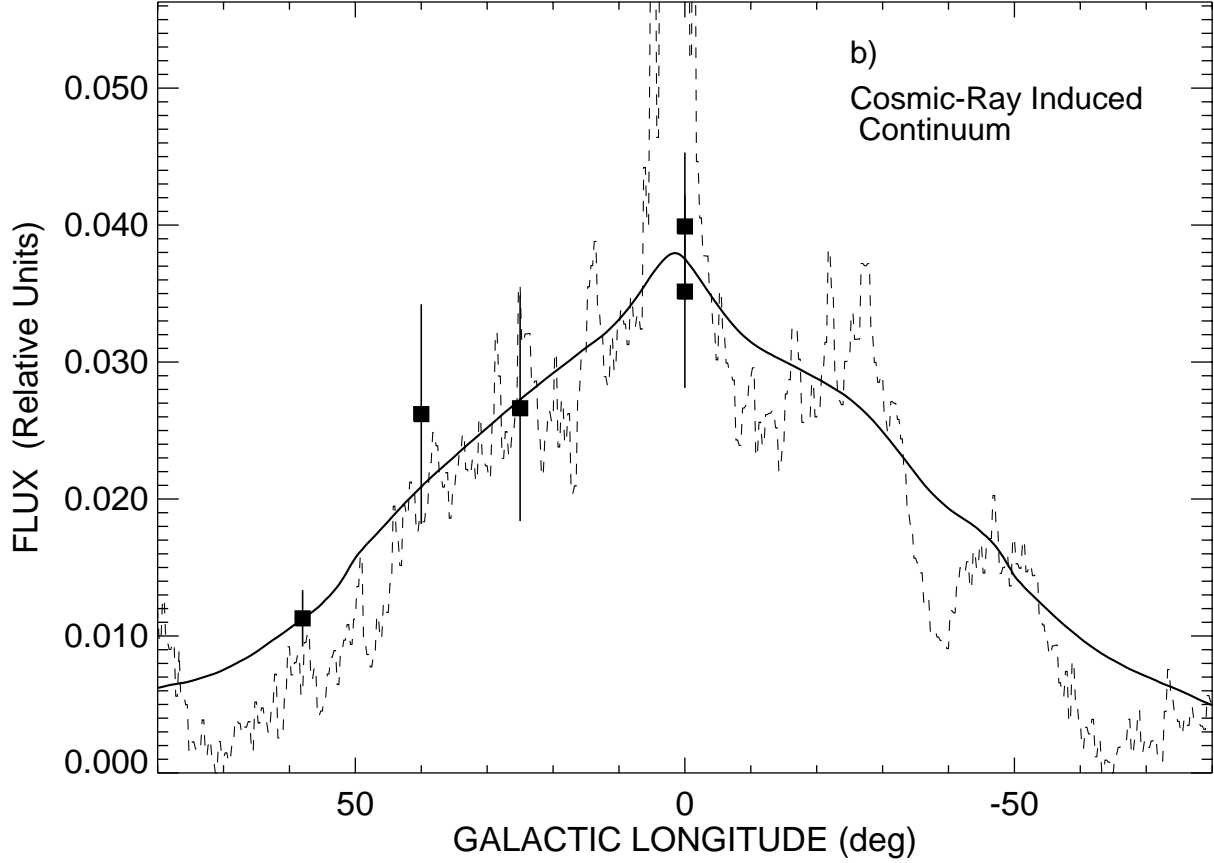


Fig. 3.— a). Longitude distribution of the soft low-energy continuum component, along with the galactic plane CO distribution as smoothed by the OSSE collimator (solid line), for comparison. The smoothed curve is normalized to the lowest-intensity galactic center observation where variable discrete source contributions were small. The unsmoothed CO distribution is shown by the dashed line. b). A similar distribution of the cosmic-ray induced component (at 2 MeV), along with the smoothed CO distribution (normalized to the average of the two galactic-center observations).

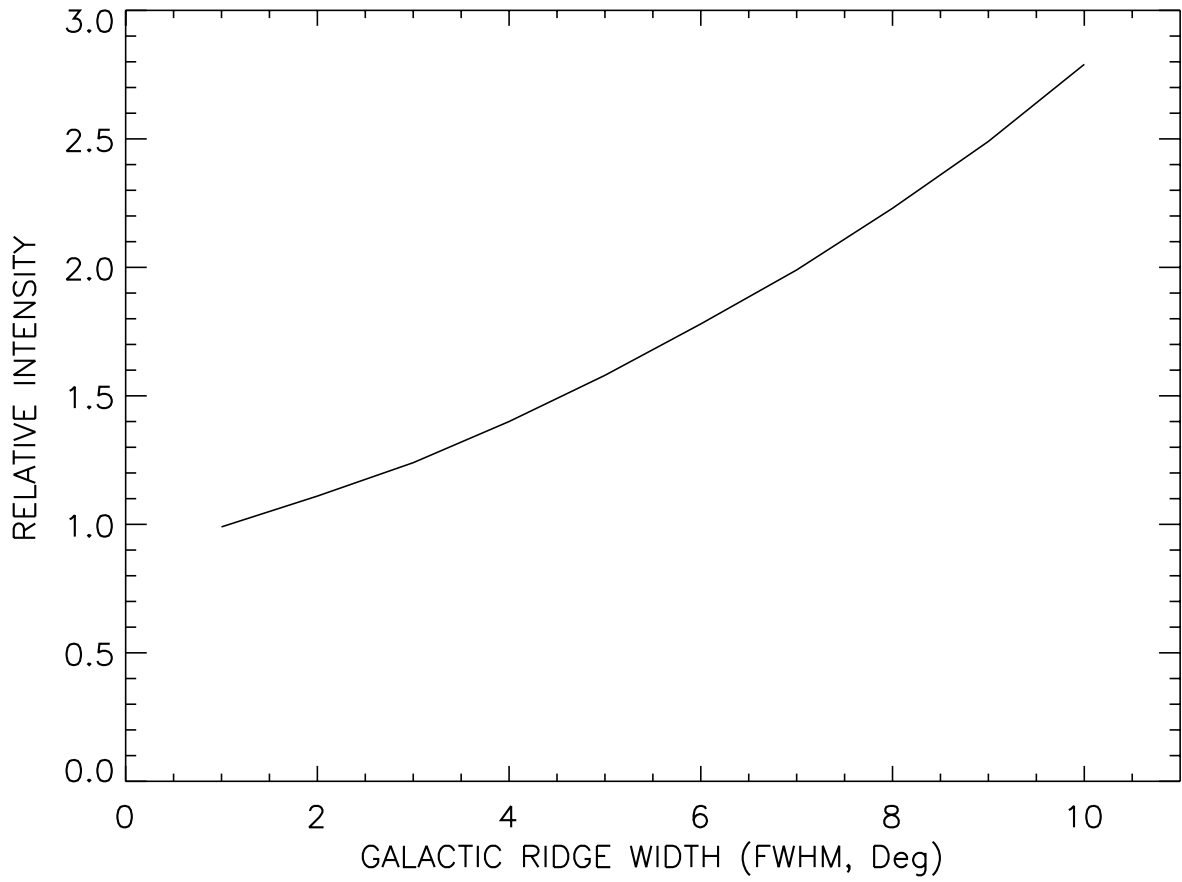


Fig. 4.— Relative intensity of the galactic ridge "line" source as observed by OSSE as a function of its assumed Gaussian width (relative units).

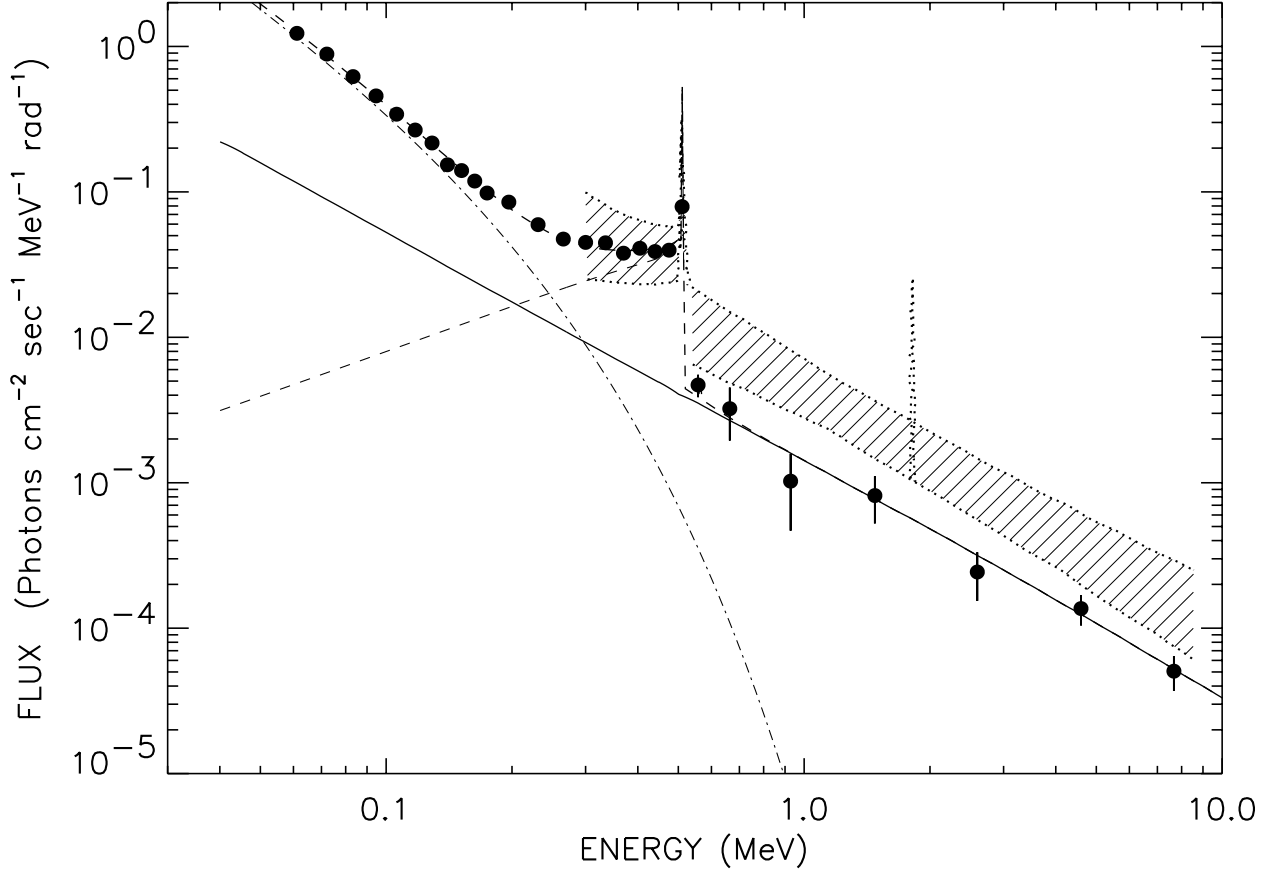


Fig. 5.— Comparison of the average OSSE spectrum (sum of VP 5 plus VP 16) measured from directions near the galactic center (11.4° FWHM field of view in longitude, 3.8° FWHM in latitude), shown by the filled circles, and SMM Gamma-Ray Spectrometer measurements (Harris et al. 1990) of the flux from the broad galactic center region (130° FWHM circular field of view). The cross-hatched areas represent the range of systematic uncertainties in the SMM flux, while the fitted components of the OSSE spectrum are shown as in Fig. 1a.

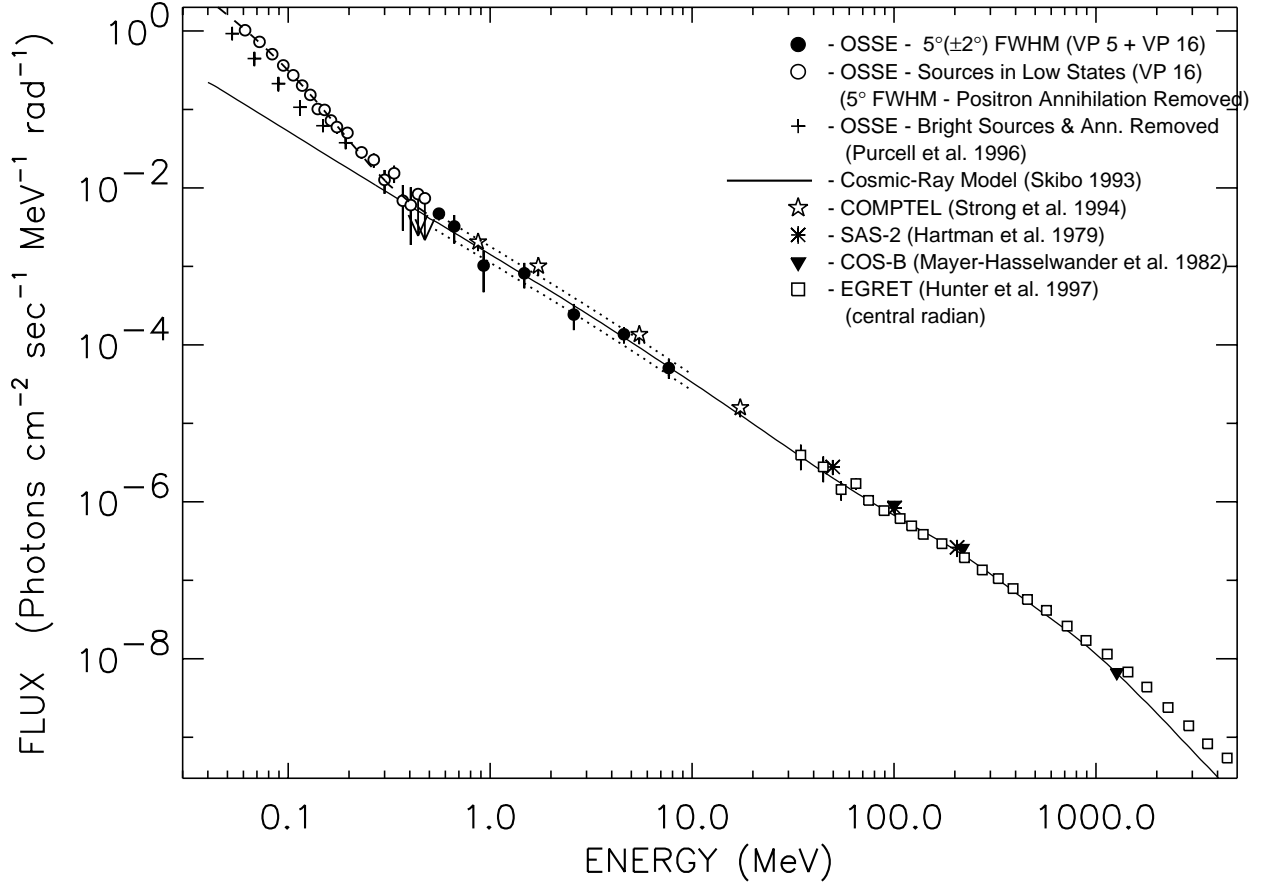


Fig. 6.— Comparisons of the OSSE estimates of the diffuse galactic ridge spectrum, less the positron annihilation components and bright source components, with other *CGRO* measurements, and with selected high-energy observations. Filled circles are the average of the OSSE galactic center observations (VP5 + VP16). The open circles are from VP 16 only, where the variable bright sources were in a low state. Crosses are OSSE galactic center observations minus contributions from 5 bright sources simultaneously observed by SIGMA (Purcell et al. 1996), and minus the positron annihilation components. The best-fit OSSE model for the soft low-energy component is shown by a dashed line. The solid line shows the cosmic-ray induced component of Skibo (1993) fit to the OSSE observations for a 5° FWHM galactic ridge distribution. The parallel dotted lines are fits to the OSSE data unfolded assuming a 7° width (upper curve), and 3° width (lower curve). Measurements are shown at overlapping energies by COMPTEL (open stars), and at higher energies by EGRET (open squares), COS B (solid triangles), and SAS 2 (asterisks).

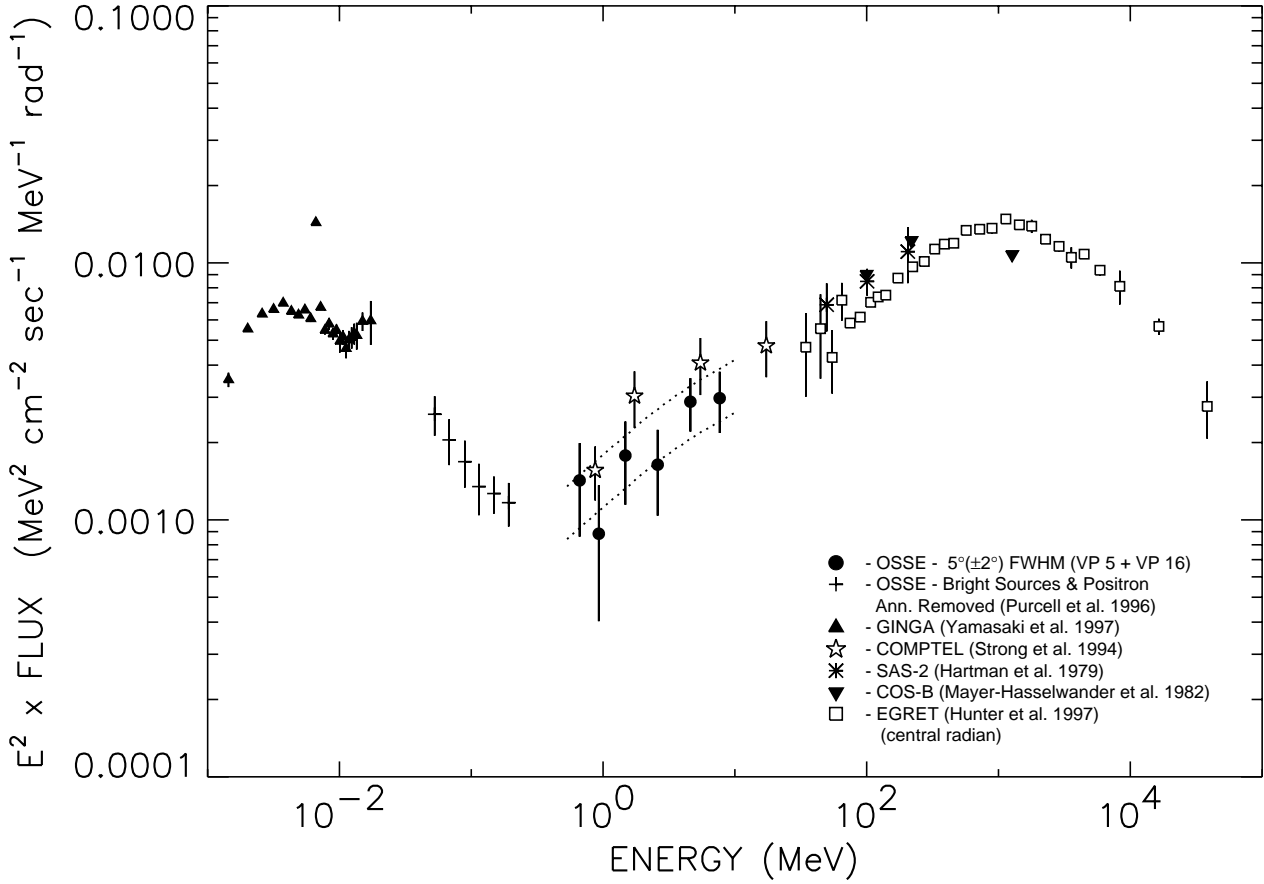


Fig. 7.— Spectral energy density plot of the OSSE observations, with 5 bright discrete source contributions below 500 keV and positron annihilation contributions subtracted, and selected earlier measurements of the diffuse spectrum from the inner galactic ridge between 1 keV and 50 GeV.