THE ASTROPHYSICAL JOURNAL, 407:597–605, 1993 April 20

GAMMA-RAY OBSERVATIONS OF THE GALACTIC CENTER: REMOVING THE GALACTIC RIDGE CONTRIBUTION

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Received 1992 July 13; accepted 1992 October 23

ABSTRACT

We combine, for the first time, spectral measurements of the emission from the disk of our Galaxy from keV to GeV energies. This emission is found to have a similar spatial distribution at all energies: a longitude extent of about $\pm 40°$ and a latitude extent of $\lesssim 5°$. Hence the name "Galactic ridge" is appropriate. The energy flux from the ridge is about 10^{-7} ergs cm^{-2} s^{-1} which gives a luminosity of about 10^{38} ergs s^{-1} assuming an effective distance to the emitting region of 3 kpc. The emission over most of the energy range is dominated by cosmic-ray electrons and protons interacting with interstellar matter. Observations by *HEAO* A-4 from 1977 to 1979 and by the GRIS balloon instrument in 1988 October give estimates of the ridge spectrum near 100 keV. We subtract this diffuse component from Galactic center observations made by wide-field ($\sim 20°$) gamma-ray instruments over the past 20 years to determine the emission from point sources in the region. For most of the measurements, the Galactic ridge accounts for between one-third and one-half of the observed flux. This solves the long-standing puzzle of why the wide-field flux is higher than that from the known point sources. Most of the measurements ($\sim 80\%$) have a flux at 100 keV, which, after substraction of our estimate of the diffuse component, is less than or equal to the sum of the normal-state fluxes from the two brightest gamma-ray sources in the region, 1E 1740.7−2942 and GRS 1758−258. These have probably been the dominant gamma-ray point sources in the region since the late 1960s. Subtracting the diffuse emission and the GRS 1758−258 emission from the HEXAGONE observations on 1989 May 22 gives a spectrum that is dominated by lines from positron annihilation.

Subject headings: galaxy: center — gamma rays: observations

1. INTRODUCTION

In this paper we study the gamma-ray emission from point and diffuse sources in the Galactic center region. Previous X-ray and gamma-ray observations are combined with new low-energy gamma-ray data to address the following questions:

1. What is the spatial extent and spectrum of the diffuse emission from the Galaxy in the low-energy gamma-ray band?
2. What is its relation to the X-ray and high-energy gamma-ray Galactic ridge?
3. What has the point-source activity been in the Galactic center region over the last 20 years?

The diffuse Galactic ridge has been previously observed in X-rays (Worrall et al. 1982; Warwick et al. 1985; Koyama et al. 1986; Kawai et al. 1988), low-energy gamma rays (Wheaton 1976; Gilman et al. 1978; Mandrou et al. 1980; Harris et al. 1990; Briggs 1991), and medium- to high-energy gamma rays (Bertsch & Kniffen 1983; Agrinier et al. 1981; Kniffen & Fichtel 1981; Paul et al. 1978). In the X-ray band there are two components to the diffuse emission. The first is a bright peak at the Galactic center extending over a region of about 1°.5 diameter (Yamauchi et al. 1990; Skinner et al. 1987; Kawai et al. 1988). The second is a narrow ($< 5°$) band or ridge of emission along the Galactic plane extending approximately $\pm 40°$ from the Galactic center observed by *EXOSAT* (Warwick et al. 1985), *HEAO 1* (Worrall et al. 1982), *SPARTAN 1* (Kawai et al. 1988), *Tenma* (Koyama et al. 1986), and *Ginga* (Koyama et al. 1989). An iron line at 6.7 keV is seen for both components (particularly intense for the central peak) suggesting a thin, hot ($\sim 10^8$ K) plasma origin (Koyama et al. 1989; Yamauchi et al. 1990; Koyama et al. 1986).

In the low-energy gamma-ray band there are many observations consistent with the presence of diffuse emission from the Galactic disk but little information on its spatial extent. The fact that instruments with different fields of view, and in most cases large ($> 20°$) fields of view, observe similar spectra when plotted per radian of Galactic longitude (see, e.g., Harris et al. 1990) indicates that the emission extends over several tens of degrees on either side of the Galactic center. Such an extended emission is seen by *HEAO* A-4 (Peterson et al. 1990). The latitude extent of the emission is $\sim 5°$ in the hard X-ray band (Wheaton 1976), but unmeasured for MeV gamma rays. The low-energy gamma-ray observations were mostly made with nonimaging wide-field instruments and, therefore, may have point-source contributions. This is particularly a problem for diffuse measurements below 100 keV because of the large number of hard X-ray sources near the Galactic center. The GRIS observation discussed in this paper was made 25° away from the center and is less susceptible to point-source contamination.

At energies greater than 35 MeV, *SAS 2* (Kniffen & Fichtel 1981) and *COS B* (Paul et al. 1978) mapped the Galactic disk. They observed strong diffuse emission extending over approximately $\pm 40°$ in Galactic longitude from the center. The latitude distribution is dominated by a component narrowly ($< 2°$) confined to the Galactic plane, plus a weaker broad ($\sim 10°$) component (Mayer-Hasselwander et al. 1982).

Theoretical studies of gamma rays from the Galactic plane (Kniffen & Fichtel 1981; Sacher & Schönfelder 1984; Skibo & Ramaty 1992) identify several components important in different energy ranges. At energies greater than about 100 MeV, the dominant emission is from the decay of π° produced by interactions between high-energy cosmic-ray nucleons and interstellar matter. Between ~ 30 keV and 100 MeV, both bremsstrahlung of cosmic-ray electrons with interstellar matter and inverse Compton scattering of 2.7 K blackbody, infrared, and starlight photons by cosmic-ray electrons are thought to be contributing processes. At X-ray energies (< 10 keV), the origin of the Galactic ridge emission is not well understood. Possible contributors are thermal bremmstrahlung from hot interstellar gas, unresolved point sources, bremsstrahlung from cosmic-ray electrons, or Compton scattering by cosmic-ray electrons.

For point sources in the Galactic center region, recent monitoring of the Galactic center region by the *Granat* hard X-ray and gamma-ray imaging instruments has shown that almost all sources within a few degrees of the center are variable (Sunyaev et al. 1991a). These include 1E 1740.7−2942, GRS 1758−258, GX 1+4, and the newly discovered (Grindlay, Covault, & Manandhar 1992) transient EXS 1737.9−2952. Other observations by imaging and scanning instruments over the past 25 years (Riegler, Boldt, & Serlemitsos 1968; Lewin, Clark, & Smith 1968; Ricker et al. 1976; Matteson 1982; Knight et al. 1985; Skinner et al. 1987, 1991; Cook et al. 1991; Bazzano et al. 1992b; Covault, Manandhar, & Grindlay 1991) give occasional snapshots of the point sources in the region. The source that frequently dominates the region at energies above 30 keV is 1E 1740.7−2942 (Sunyaev et al. 1991a; Bouchet et al. 1991; Cook et al. 1991; Skinner et al. 1987). The similarity of the spectrum of this source with that of Cyg X-1 (Sunyaev et al. 1991a; Cook et al. 1991) indicates that it may be a black hole. It has also exhibited a strong, broad spectral line that appeared in 1 day's data from *Granat/SIGMA* on 1990 October 13–14 and lasted less than 4 days (Bouchet et al. 1991). The line energy of 480 keV suggests an origin in positron annihilation.

Less is known about GRS 1758−258. Prior to *Granat* observations (Sunyaev et al. 1991b), it was confused with GX 5−1. It has a hard spectrum (photon power-law index ≈ −1.8) and is known to be variable. The hard spectrum and lack of pulsations suggest that it may also be a black-hole system. GX 1+4 is an X-ray pulsar with 4 minute period. It is highly variable with periods of activity in the late 1970s (see, e.g., McClintock & Leventhal 1989) and 1990s (Sunyaev et al. 1991c).

In addition to the imaging observations, there are more than a dozen gamma-ray observations of the Galactic center since 1968 by wide (> 10° FWHM) field-of-view instruments. These wide-field measurements can, in principle, be used to determine the sum of the gamma-ray emission from point sources in the region. Efforts to do this in the past (Matteson 1982) were inhibited by an uncertain knowledge of the diffuse continuum emission from the Galactic disk. In this paper we use data recently published from *HEAO* A-4 (Peterson et al. 1990) and an observation (Tueller et al. 1992; Gehrels et al. 1991) by the balloon-borne Gamma-Ray Imaging Spectrometer (GRIS) to estimate the diffuse continuum component. We then subtract this component from the historical wide-field measurements to obtain the first estimate of the long-term light curve of point-source flux from the Galactic center region.

In § 2 of this paper we combine spectral measurements of the Galactic ridge from X-rays through GeV gamma rays. Aspects of the emission common to all wavelengths are noted. In § 3 the ridge component is subtracted from wide-field observations of the Galactic center in low-energy gamma rays to study point sources in the region. Section 4 presents discussion on both topics, and § 5 concerns future observations. Preliminary results of the point-source analysis are given by Gehrels & Tueller (1992).

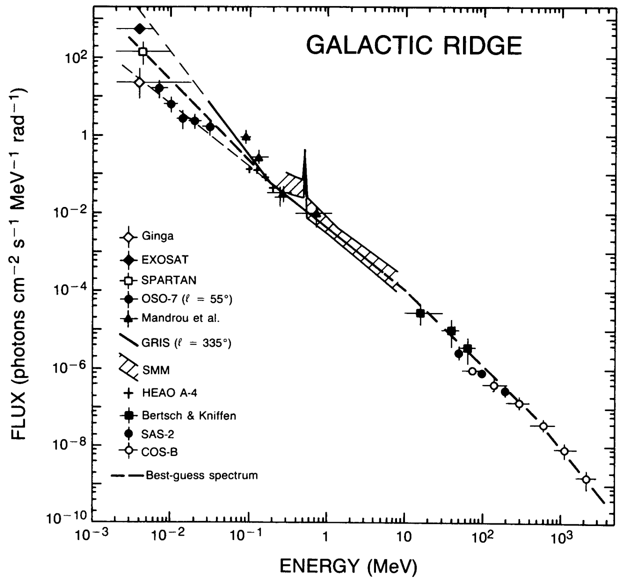

FIG. 1.—Broad-band spectrum of the diffuse Galactic ridge. *EXOSAT* (Warwick et al. 1985); *SPARTAN 1* (Kawai et al. 1988); *Ginga* (Koyama et al. 1989); *OSO 7* (Wheaton 1976); Mandrou et al. (1980); GRIS (Tueller et al. 1992); *SMM* (Harris et al. 1990); *HEAO* A-4 (Briggs 1991); Bertsch & Kniffen (1983); *SAS 2* (Kniffen & Fichtel 1981); *COS B* (Paul et al. 1978). The dashed lines (see Table 1 for parameters) are a best-guess representation of the overall spectrum.

2. GALACTIC RIDGE

Spectral measurements of emission from the Galactic disk are shown in Figure 1. Except as noted for *OSO 7* and GRIS, the observations were centered on $l = 0°$. At high energies (> 10 MeV) the data are reasonably unambiguous. The measurements are consistent with one another and were made by imaging instruments that allowed subtraction of point-source contributions. The spatial extent of the emission is also well defined (see § 1).

In the intermediate energy range (10 keV–10 MeV) the spectrum and spatial extent are not as well measured. Most of the data in this range are from wide-field (∼ 20°) observations near the Galactic center that can have significant contamination from point sources. The data we have chosen to plot in Figure 1 are least susceptible to this problem. They are from instruments that have either scanning capabilities to separate out the point sources (*HEAO* A-4) or large fields of view so the diffuse flux dominates (∼ 45° for Mandrou et al. 1980; 130° for *SMM*), or that were observing away from the center (GRIS at $l = 335°$; *OSO 7* at $l = 55°$).

For the point-source study in the next section we require a value for the diffuse flux at 100 keV. Both the GRIS and *HEAO* A-4 data should be good for this purpose (see, e.g., Smith et al. 1992), and the factor of 2 difference between them (GRIS flux = 0.31 photons cm^{-2} s^{-1} MeV^{-1} rad^{-1}; *HEAO* A-4 flux = 0.17 photons cm^{-2} s^{-1} MeV^{-1} rad^{-1}) is a reasonable estimate of the range of uncertainty. The GRIS spectrum (Tueller et al. 1992; Gehrels et al. 1991) shown in Figure 2 was obtained on 1988 October 29 from a point in the Galactic plane 25° west of the center ($l = 335°$). It is well fitted by a broken power law with the break at 182 keV, plus a narrow 511 keV line of flux $(1.8 \pm 0.8) \times 10^{-4}$ photons cm^{-2} s^{-1} (Tueller et al. 1992). Conversion to flux per radian of the Galactic plane was done by dividing by the instrument field of

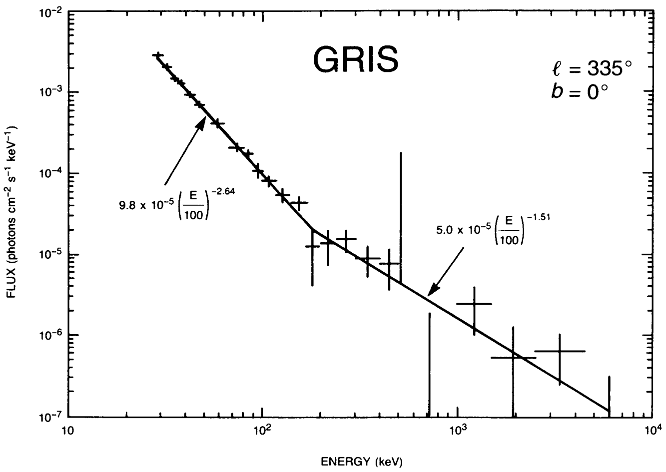

FIG. 2.—Galactic plane ($l = 335°$, $b = 0°$) spectrum observed by GRIS on 1988 October 29. Errors are ± 1 σ statistical uncertainties. The best two-power-law fit is shown with a break at 182 keV. The fit also includes a narrow line at 511 keV.

view of 0.31 rad (18°) FWHM below 100 keV increasing to ~0.4 rad (23°) FWHM in the MeV range. For the purpose of subtracting diffuse continuum from historical wide-field measurements, the advantage of the GRIS $l = 335°$ Galactic plane data is that they were obtained with a similar instrument and a similar observing technique to those of the historical measurements. The disadvantages are that they are off the center and that they may include point sources. However, the observation was close to the center and the diffuse distribution is thought to be fairly flat in Galactic longitude (Peterson et al. 1990; see also discussion below). Also, the only known strong gamma-ray source in the field of view is GX 339−4 which was in its gamma-ray low state (X-ray high state) in 1988 October. *Ginga* observed it at a count rate of 0.65 counts cm^{-2} s^{-1} (flux ≈ 380 μJy) in the 1–6 keV energy band (Miyamoto et al. 1991) which puts it in the high X-ray, low gamma-ray state. At low energies ($\lesssim$40 keV) there probably is some contamination of the GRIS data by the numerous X-ray sources in the Galactic plane.

The *HEAO* A-4 spectrum and spatial information for the diffuse Galactic emission are from Peterson et al. (1990). The data were obtained during three complete sky scans made between 1977 August and 1979 February with the MED detector system (80 keV–2 MeV range; 16° field of view). Contributions to the measured sky maps from the eight brightest known Galactic point sources were fitted and subtracted. The longitude distribution of the residuals within 20° latitude of the Galactic plane is shown in Figure 3, which is reproduced from Peterson et al. (1990). Also shown for comparison is the *COS B* 100 MeV gamma-ray distribution as smoothed by Mahoney et al. (1984). The *HEAO* A-4 data are a reasonable estimate of the longitude distribution of the diffuse Galactic emission, but may still have contributions from unresolved point sources. The longitude distribution is seen to be broad with a width of about ±60°. It has a somewhat similar shape to the 100 MeV distribution, with the exception of an excess at ~40° and a deficit in the anticenter direction. The spectral points shown in Figure 1 are the net flux in the central region. They are lower than the GRIS spectrum at 100 keV by a factor of 2–3.

There is also some inconsistency between different observations near 1 MeV. The GRIS and *SMM* spectra shown in Figure 1 are above the upper limits from *HEAO 3* (Riegler et al. 1985) in Spring 1980 (see Harris et al. 1990). This disagreement is at about the 4 σ significance level. If the GRIS and *SMM* are of truly diffuse emission, then there should not be lower measurements. It may be that the background subtraction method for the *HEAO 3* Galactic plane scans includes some diffuse flux in the background; it may be that the GRIS and *SMM* measurements are including some point sources.

The *OSO 7* observation gives the only data between 10 and 30 keV. The points in Figure 1 are from Wheaton (1976) converted to units "per radian" using the measured latitude extent in each energy band (typically 4°). This was a scanning observation and should give a reasonable estimate for the diffuse emission. However, the measurement was made at $l = 55°$ and may have a lower flux than that at $l = 0°$. Note, though, that if the excess at $l \approx 40°$ in the *HEAO* A-4 data (Fig. 3) is true diffuse emission, then the *OSO 7* flux could actually be higher than that at $l \approx 0°$. The *OSO 7* data are also important because they show that the emission is narrowly confined ($\lesssim 5°$) in latitude. More definitive observations of spatial distributions and spectra are clearly needed between 10 keV and 1 MeV.

The same can be said for the X-ray band. In this case, there are several observations but only poor information on the spatial extents and spectra. Published longitude distributions from *EXOSAT* (Warwick et al. 1985), *Tenma* (Koyama et al. 1986); and *Ginga* (Koyama et al. 1989) show that the emission extends approximately ±40° from the Galactic center. The *EXOSAT* data indicate that the emission is narrowly confined to the Galactic plane with a latitude spread of only about 2° FWHM. Spectra have generally not been published. The points in Figure 1 were calculated from quoted net luminosities using assumptions for the spectral shapes (E^{-2} photon power law) and spatial distribution. There is currently more than a factor of 10 uncertainty in the X-ray flux from the Galactic ridge.

The heavy dashed line in Figure 1 represents our best guess for the overall spectrum of the Galactic ridge emission. The light dashed lines below 180 keV give a range of uncertainty. The parameters for these lines are given in Table 1.

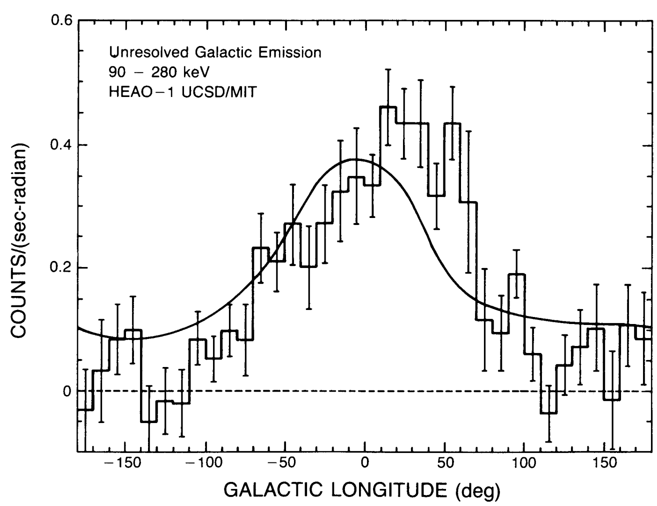

FIG. 3.—*HEAO* A-4 distribution in Galactic longitude of 90–280 keV emission after removal of known point sources. The curve is a smoothed representation (Mahoney et al. 1984) of the ~100 MeV emission profile, normalized near the center (from Peterson et al. 1990).

TABLE 1

PARAMETERS FOR BEST-GUESS GALACTIC RIDGE SPECTRUM[a]

E_1 (MeV)	E_2 (MeV)	F_0[b] (photons cm^{-2} s^{-1} MeV^{-1} rad^{-1})	γ[b]
0.003	0.18	2.0×10^{-3}	2.05
		(low 4.4×10^{-3})	(low 1.59)
		(high 7.2×10^{-4})	(high 2.64)
0.18	10	4.4×10^{-3}	1.59
10	600	1.1×10^{-2}	1.96
600	2000	3.3×10^{-1}	2.49

[a] Dashed line in Fig. 1.
[b] Flux = $F_0(E/1 \text{ MeV})^{-\gamma}$.

3. GALACTIC CENTER POINT SOURCES

In this section we subtract the Galactic ridge component from gamma-ray observation of the Galactic center made with wide field-of-view instruments. The heavy dashed line in Figure 1 (parameters in Table 1) was used as the diffuse spectrum, with uncertainty ranges determined from the light dashed lines. The 12 observations used in this analysis are listed in Table 2. Observations by instruments with fields of view greater than 40° were not included due to uncertainties in the Galactic longitude distribution of the diffuse disk spectrum beyond the central radian. A few observations were not included due to the unavailability of detailed spectral data. Note that the 1988 October 28 GRIS observation in Table 1 is not the one of the Galactic plane discussed in § 2. Two observations were made during the 1988 October 28–29 GRIS flights, one of the Galactic center and the other of the $l = 335°$ position in the Galactic plane.

The procedure used in the analysis was to digitize the published energy spectrum from each observation, subtract off the ridge component and fit the residual. Examples are shown in Figure 4 and 5, where the original and residual spectra are both plotted. The ridge component was calculated by multiplying the heavy dashed spectrum in Figure 1 by the FWHM fields of view of the instruments (Table 2 converted to radians). The residuals represent the sum of the spectra of point sources within the fields of view. We fit the residual spectra up to ~150 keV with a power law of the form $A(E/100 \text{ keV})^{-\alpha}$.

Some surprising results are obtained in this analysis. For several of the observations (1968.31, 1974.25, 1980.2, 1989.39) the ridge component is found to contribute more than half of the continuum emission. For most of the measurements, this component contributes at least one-third of the total observed flux. Thus, we now understand why the flux is so high in these wide-field observations. It was initially thought (Matteson 1982) that a combination of point sources made up the total. However, later imaging observations (e.g., Cook et al. 1991) did not see enough point-source flux. The answer to this puzzle is diffuse or unresolved emission. The wide-field instruments detect the diffuse flux and hence see a high total flux, while the imaging instruments are not sensitive to this component. Also, we will show below that the magnitude of the diffuse flux is about right; the residual flux when the ridge component is subtracted from the wide-field measurements is consistent with fluxes from known point sources.

A particularly interesting case where the component dominates is the 1989 May 22 (1989.39) HEXAGONE spectrum shown in Figure 6. The histogram in the figure has both the diffuse flux and the flux from GRS 1758−258 subtracted from it. A POKER balloon observation (Bazzano et al. 1992a) just five days before the HEXAGONE flight showed that GRS 1758−258 was in the same intensity state that was observed by *Granat* (Sunyaev et al. 1991b) in 1990 March/April. The histogram in Figure 6 therefore represents the spectrum from other Galactic center sources, possibly dominated by 1E 1740.7−2942. The 130–180 keV feature observed (Slassi et al. 1991; Smith et al. 1992) in the spectrum becomes more prominent with the diffuse disk emission subtracted. The residual spectrum has a prominent maximum at ~170 keV. This feature has been interpreted (Lingenfelter & Hua 1991) as a Compton backscatter peak from an accretion disk or cloud

TABLE 2

WIDE-FIELD OBSERVATIONS OF THE GALACTIC CENTER

Date	Date	Instrument	Field of View[a] (FWHM)	Point-Source Flux at 100 keV, A[b] (10^{-4} photons cm^{-2} s^{-1} keV^{-1})	Point-Source Power Law α[b]	511 keV Line Flux[c] (10^{-4} photons cm^{-2} s^{-1})	Reference
1968 Apr 23	1968.31	Rice Univ.	24°	0.2 (−0.2 to 0.3)	4 (3–5)	...	Haymes et al. 1969
1970 Nov 25	1970.90	Rice Univ.	24	1.06 (0.71–1.24)	3.2 (2.7–3.3)	6.7 ± 1.9	Johnson et al. 1972
1971 Nov 20	1971.89	Rice Univ.	24	1.23 (0.85–1.44)	3.4 (3.4–3.5)	6.7 ± 1.9	Johnson & Haymes 1973
1974 Apr 1–2	1974.25	Rice Univ.	13	0.51 (0.31–0.62)	3.3 (3.0–3.3)	8.0 ± 3.2	Haymes et al. 1975
1977 Nov 11–12	1977.86	Bell/Sandia	15	2.04 (1.79–2.17)	2.6 (2.5–2.7)	12.2 ± 2.2	Leventhal et al. 1978
1979 Apr 15	1979.29	Bell/Sandia	15	1.18 (0.94–1.31)	2.6 (2.1–2.7)	12.4 ± 4.3	Leventhal et al. 1980
1979 Sep/Oct	1979.8	*HEAO 3*	~30	1.87 (1.41–2.10)	3.1 (2.8–3.1)	18.5 ± 2.1	Riegler et al. 1985
1980 Mar/Apr	1980.2	*HEAO 3*	~30	0.80 (0.28–1.04)	2.9 (1.2–3.0)	6.5 ± 2.7	Riegler et al. 1985
1981 Nov 20	1981.89	Goddard	15	1.27 (1.03–1.41)	2.9 (2.7–3.0)	0.0 ± 6.0	Paciesas et al. 1982
1988 May 1	1988.33	GRIS	17	1.08 (0.78–1.24)	3.2 (2.8–3.3)	7.5 ± 1.7	Tueller et al. 1992, Gehrels et al. 1991
1988 Oct 28	1988.83	GRIS	17	1.42 (1.09–1.58)	2.5 (2.0–2.5)	11.8 ± 1.6	Tueller et al. 1992, Gehrels et al. 1991
1989 May 22	1989.39	HEXAGONE	19	0.45 (0.06–0.65)	3.0 (2.0–3.0)	8.9 ± 2.7	Slassi et al. 1991, Chapuis et al. 1991

[a] At 100 keV.
[b] Fit to residual point-source flux after diffuse flux is subtracted. Flux = $A(E/100 \text{ keV})^{-\alpha}$. The value corresponds to subtraction of the heavy-dashed diffuse spectrum in Fig. 1. The range in parentheses is for the range of diffuse spectra indicated by the light-dashed curves in Fig. 1. The fit is for data points up to ~150 keV. In a few cases, the lowest one or two data points were excluded (see Figs. 4–5).
[c] From Lingenfelter & Ramaty 1989. Line fluxes for 1988.33 and 1988.83 are from Gehrels et al. 1991 and for 1989.39 from Chapuis et al. 1991, (but see also Wallyn et al. 1992).

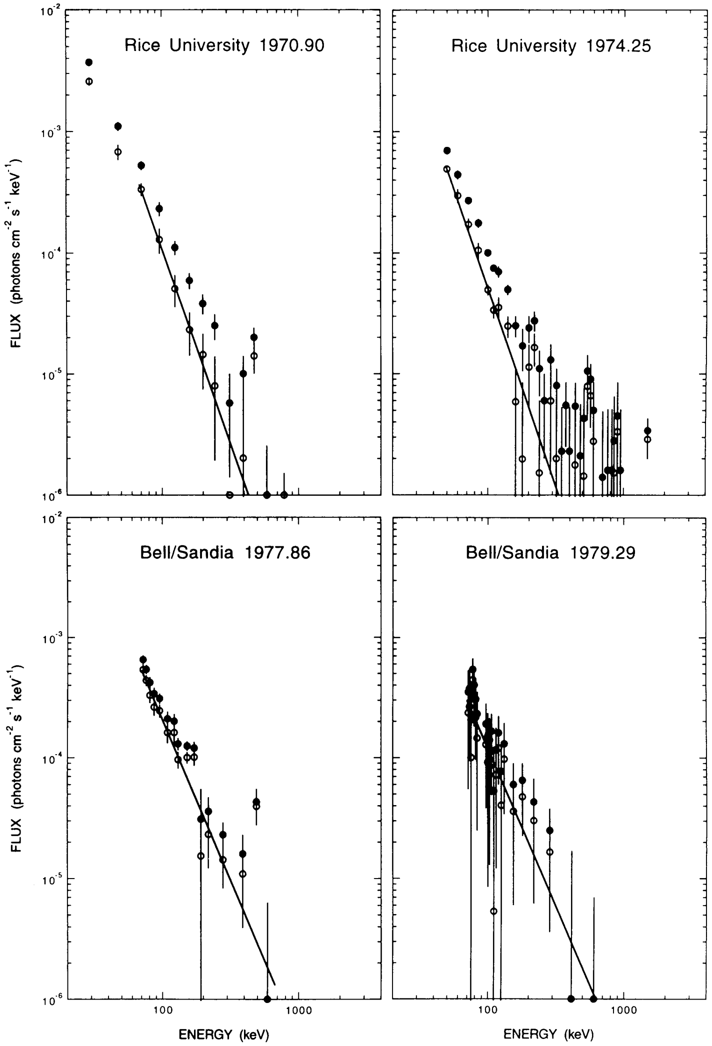

FIG. 4

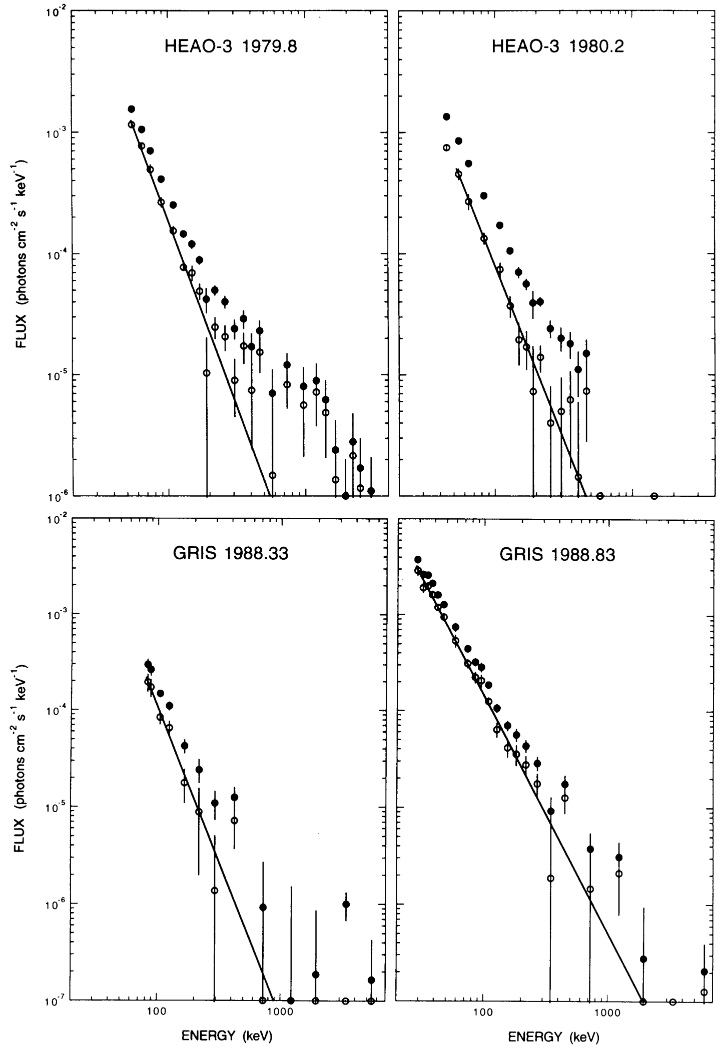

FIG. 5

FIG. 4.—Measured Galactic center spectra (*filled circles*) and residual spectra (*open circles*) for four observations. The residual spectra were calculated by subtracting the Galactic ridge contribution (heavy dashed line in Fig. 1). Data points for narrow 511 keV lines are not plotted (see Table 2 for line intensities). The lines in the figure are power-law fits to the residual spectra up to ~150 keV (excluding low-energy points in some cases). References and parameters for the fits are given in Table 2.

FIG. 5.—Same as Fig. 4. Open circles without error bars at the bottom of the plot correspond to negative points where the subtracted diffuse flux was higher than the measurement. This is particularly noteworthy for the *HEAO 3* 1980.2 spectrum as discussed in the text.

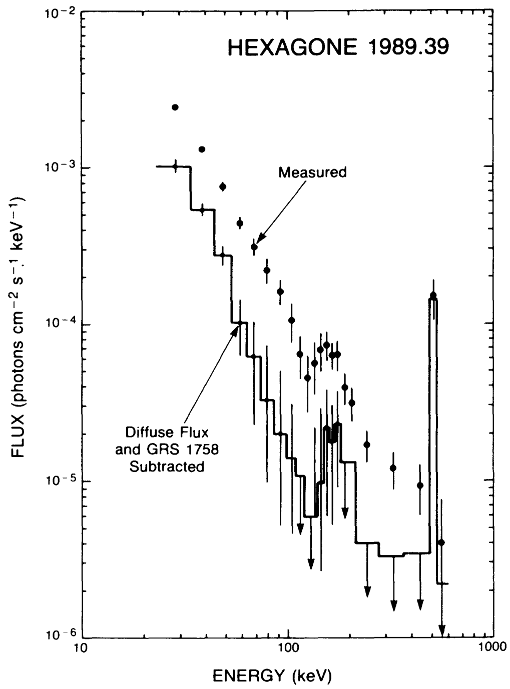

FIG. 6.—Measured Galactic center spectrum (*filled circles*) and residual spectrum (histogram) for the HEXAGONE observation in 1989. The residual spectrum has both diffuse flux (heavy dashed line in Fig. 1) and GRS 1758−258 subtracted from it. The GRS 1758−258 spectrum was assumed to be $1.6 \times 10^{-1} E^{-1.77}$ photons cm^{-2} s^{-1} keV^{-1} (Sunyaev et al. 1991b; Bazzano et al. 1992a).

surrounding a source of 511 keV positron annihilation photons. Evidently, on 1989 May 22 the dominant gamma-ray emission from the Galactic center region was in two lines (170 and 511 keV), both associated with positron annihilation.

The results of the fits (flux at 100 keV, A, and spectral slope, α) to the residual spectra are listed in Table 2. Also listed are the fluxes for the positron annihilation line at 511 keV. There is no clear correlation between the continuum and line fluxes. There are times when the line flux is high and the continuum is close to zero (1989.39) and vice versa (1981.89). The residual continuum fluxes at 100 keV from Table 2 are plotted in Figure 7 as a function of time. The error bar for each observation represents the range of the residuals after subtracting the high and low limits for the diffuse spectrum (Table 1). Also shown for comparison is the flux at 100 keV for the sources 1E 1740.7−2942, GRS 1758−258, and the sum of the two. The GRS 1758−258 is from the 1990 *Granat*/SIGMA observations (Sunyaev et al. 1991b). The flux for 1E 1740.7−2942 is for its "normal" state observed by GRIP in 1988 (Cook et al. 1991) and 1989 (Grunsfeld et al. 1991), *MIR*/HEXE (Skinner et al. 1991) in 1989, EXITE in 1989 (Covault et al. 1991) and *Granat*/SIGMA (Sunyaev et al. 1991a; Bouchet et al. 1991) in 1990. A line is not shown in the figure for GX 1+4, which can also have significant 100 keV flux (see, e.g., Levine et al. 1984). The source is highly variable with periods of high activity in the late 1970s (see, e.g., McClintock & Leventhal 1989). The 100 keV flux during the high states is $\sim 4 \times 10^{-4}$ photons cm^{-2} s^{-1} keV^{-1} (Ricker et al. 1973; Levine et al. 1984), or about the same level as that shown for GRS 1758−258. The newly discovered EXS 1737.9−2952 (Grindlay et al. 1992) could also be contributing at a flux of $\sim 10^{-4}$ photons cm^{-2} s^{-1} keV^{-1}.

4. DISCUSSION

4.1. *Point Sources*

Figure 7 is the first long-term light curve ever made of the gamma-ray flux from point sources in the Galactic center region. Its usefulness is limited, though, since we cannot determine which sources are contributing at any given time. Nonetheless, several conclusions can be drawn. For one thing, the flux is quite variable, and there are times when the point-source emission is small (1968.31 and 1989.39). This implies that there are few strong point sources of 100 keV emission within $\sim 20°$ of the Galactic center and that all of them are variable.

For the times when strong emission is observed, most of the measurements have a 100 keV flux that is less than or equal to the sum of the known dominant sources in the region, namely 1E 1740.7−2942 and GRS 1758−258. Without images, we cannot prove that the sources were active over this time period, but the flux data suggest that this is the case. There are a few imaging spotchecks that support this conclusion. During the *HEAO* A-4 scans in 1977 and 1978 (Levine et al. 1984), the strong source in the Galactic center region, known then as GCX, was most likely 1E 1740.7−2942. The position is consistent and the spectrum about 100 keV is similar to the normal-state spectrum of 1E 1740.7−2942. The Spacelab-2 X-ray/hard X-ray coded aperture imager observed 1E 1740.7−2942 as the dominant hard source in the region in 1985 August (Skinner et al. 1987). Since 1988 there have been many images made of the Galactic center. The first in 1988 by the Caltech GRIP balloon instrument (Cook et al. 1991) definitely established 1E 1740.7−2942 as the dominant Galactic center gamma-ray source. Other measurements of a normal state spectrum include *MIR*/HEXE in 1989 (Skinner et al. 1991), GRIP in 1989 (Grunsfeld et al. 1991), EXITE in 1989 (Covault et al. 1991), and *Granat*/SIGMA in 1990 (Sunyaev et al. 1991a; Bouchet et al. 1991). *Granat*/SIGMA measurements in 1991

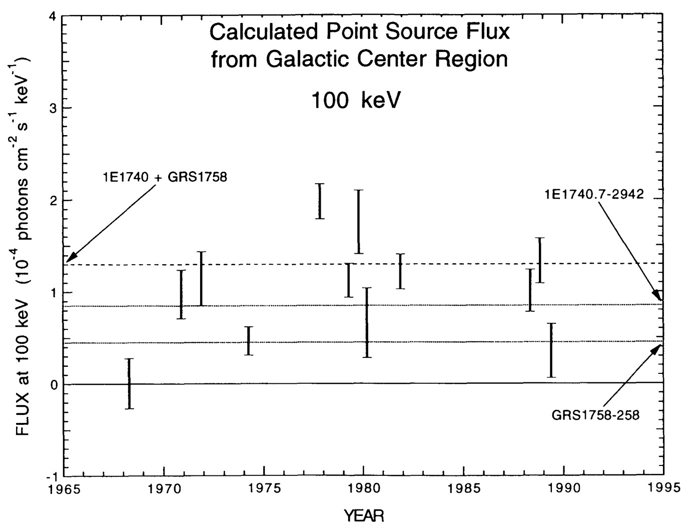

FIG. 7.—Residual point-source fluxes at 100 keV after subtraction of diffuse flux from wide field-of-view measurements. Fluxes are from Table 2. The range for each point corresponds to the range of diffuse flux shown by the light-dashed lines in Fig. 1. The 100 keV flux levels for the "normal" 1990 states (Sunyaev et al. 1991b) of 1E 1740.7−2942, GRS 1758−258, and their sum are indicated.

(Sunyaev et al. 1991a) showed 1E 1740.7−2942 in a low state, supporting our conclusions on variability.

An interesting result is obtained by combining the HEXAGONE (1989.39) residual flux with other measurements made of 1E 1740.7−2942 in early 1989. Remarkably, there are four other observations within a 2 month period that included the HEXAGONE flight: two are with imaging instruments (GRIP, Grunsfeld et al. 1991; EXITE, Covault et al. 1991), and two with narrow (<2°) field-of-view instruments (*MIR*/HEXE, Skinner et al. 1991; POKER, Bazzano et al. 1992b). A plot of the 60 keV flux from 1E 1740.7−2942 as a function of time from these observations is shown in Figure 8. The HEXAGONE data point is the residual after subtracting contributions from the diffuse Galactic ridge and from GRS 1758−258. The POKER observation (Bazzano et al. 1992a) just 5 days before HEXAGONE showed that GRS 1758−258 was active at a level near its 1990 March/April state (Sunyaev et al. 1991b). We subtracted a flux of 1.1×10^{-4} photons cm^{-2} s^{-1} keV^{-1} from HEXAGONE for GRS 1758−258. The range shown for the HEXAGONE point in Figure 8 corresponds to the range of uncertainty in the diffuse flux contribution. The upper limit is for the lower light-dashed line in Figure 1, and the point is for the heavy-dashed line. Subtracting the upper light-dashed diffuse spectrum gives a negative value with statistical uncertainty consistent with zero. Because of the uncertainty in the diffuse contribution, no strong conclusion can be drawn about a turn-off of 1E 1740.7−2942 in 1989 May. The POKER observation suggests the source was in a state of reduced emission prior to the HEXAGONE observation. If future observations of the diffuse continuum confirm a high GRIS-like flux, then the 1E 1740.7−2942 source turned off in 1989 May. If a low *HEAO*-like flux is found, then the 1E 1740.7−2942 source may have had a fairly constant flux throughout this time period. An interesting discussion of possible point-source contributions to the HEXAGONE observation is given by Smith et al. (1992).

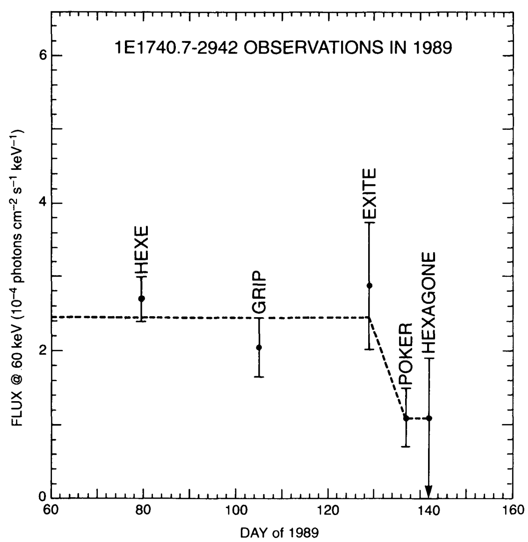

FIG. 8.—The flux at 60 keV from 1E 1740.7−2942 for observations between March 20 and May 22 in 1989 by *MIR*/HEXE (Skinner et al. 1991), GRIP (Grunsfeld et al. 1991), EXITE (Covault et al. 1991; J. Grindlay 1992, private communication), POKER (Bazzano et al. 1992b), and HEXAGONE (Slassi et al. 1991). The HEXAGONE point has diffuse flux and "normal" state flux for GRS 1758−258 subtracted.

There are two observations (1977.86 and 1979.8) that have flux levels significantly exceeding that of 1E 1740.7−2942 plus GRS 1758−258. The 1977.86 observation by Bell/Sandia was just 12 days before an observation (Knight et al. 1985) by the NRL high-energy X-ray balloon instrument, which scanned the Galactic center region. The scans revealed comparable 100 keV fluxes from sources they identify as A1742−294 and A1743−322. However, the raw scan data appear to be consistent with significant emission from 1E 1740.7−2942, a source not included in their fits. The origin of the excess emission in Figure 7 is unclear. GX 1+4 and GRS 1758−258 (GX 5−1) appear not to have been particularly active at the time. The other high observation was by *HEAO 3* in fall of 1979. There were no imaging observations near this time, so we cannot determine the source of the excess flux. It is interesting that this is the one Galactic center observation with significant excess flux above 511 keV (see Fig. 5). It is possible that this high-energy emission is from some source other than 1E 1740.7−2942 or GRS 1758−258 that was active at that time.

4.2. *Galactic Ridge*

A ridge of Galactic emission of approximately uniform shape and size is observed from the Galactic center direction over the broad spectral range from 2 keV to 2 GeV. It has a true ridge shape with broad longitude distribution and narrow latitude distribution. Below 10 keV and above 70 MeV the longitude extent is roughly ±40° with a flat-top distribution, and the latitude extent of the dominant emission is less than 5° (see, e.g., Warwick et al. 1985; Mayer-Hasselwander et al. 1982). At 100 keV there is one measurement of longitude distribution (Peterson et al. 1990) that shows a ±60° extent. Between 7 and 40 keV the latitude extent at $l = 55°$ is ~4° (Wheaton 1976).

In Figure 9 we plot the Galactic ridge spectrum multiplied by E^2 to give the energy flux per decade of photon energy. The heavy solid curve and light solid curves below 0.18 MeV represents the observations and correspond to the dashed lines in Figure 1. The other curves are for the model calculations by Sacher & Schönfelder (1984) of the bremsstrahlung, inverse Compton, and π° decay components of the emission (see also Skibo & Ramaty 1992 for recent model calculations). The bremsstrahlung spectrum is the "high" case of Sacher & Schönfelder based on a derivation by Lebrun et al. (1982) above 70 MeV and reasonable assumptions for extrapolating the cosmic-ray electron spectrum to lower energies. Below 70 MeV, a hatched area is shown due to uncertainties in the cosmic-ray electron escape times from the Galaxy: the upper bound is for 1×10^7 yr, the lower bound for 2.5×10^7 yr. The flattening of the bremsstrahlung curves below ~0.1 MeV may not really occur. If the cosmic-ray electron spectrum has a cutoff below 300 keV ($E_{e-} \approx 3E_\gamma$ for bremsstrahlung) due to ionization energy loss, then the bremsstrahlung component would fall off below ~0.1 MeV (Sacher & Schönfelder 1984), much below the curves in Figure 9.

For energies above ~0.1 MeV, the calculations and observations agree well. Bremsstrahlung appears to dominate over the inverse Compton process below 100 MeV (see also Kniffen & Fichtel 1981). The best fit is for the "high" cosmic-ray electron spectrum of Sacher & Schönfelder (1984). Above 100 MeV, the dominant process is π° decay from cosmic-ray nucleon interactions with interstellar matter. The important question of what process produces the X-ray Galactic ridges cannot be answered from the flux alone because of the large

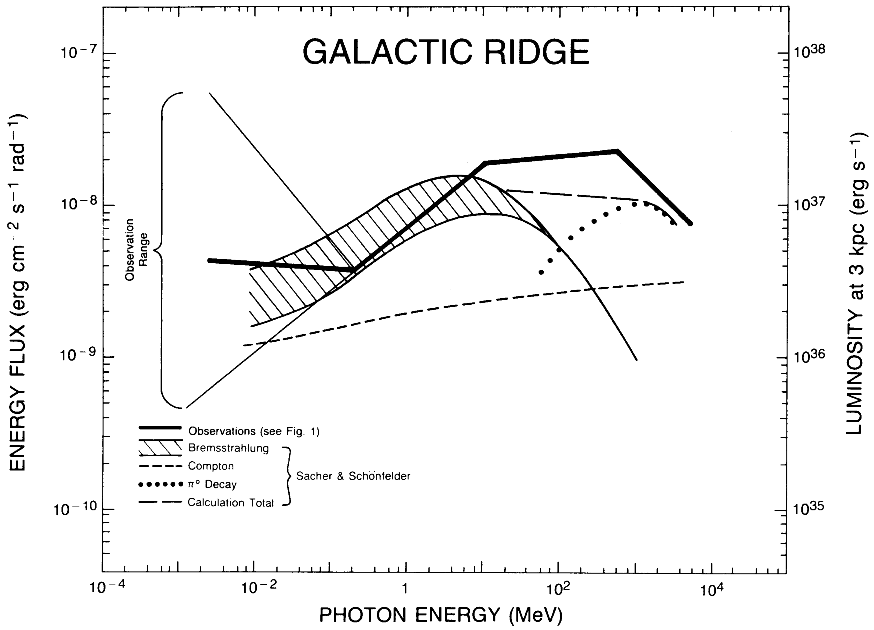

FIG. 9.—Luminosity spectrum ($E^2 \times$ flux; energy output per decade of photon energy) of the Galactic ridge. The heavy solid curve represents the observations and is the same as the dashed lines in Fig. 1. The typical data spread is a factor of 2 centered on the curve. Below 180 keV, the range of uncertainty in the observations is indicated by the light solid curves. The extrapolation below ~ 2 keV shows a falloff based on assumed attenuation by the interstellar medium. The other curves are components of the model calculations of Sacher & Schönfelder (1984). The luminosity on the right-hand axis is for an effective distance (*see text*) to the emitting region of 3 kpc and an extent in Galactic longitude of roughly 1 rad.

uncertainties in the data. The 6.7 keV iron line observed from the ridge indicates that the emission may be thermal bremsstrahlung from an optically thin hot ($\sim 10^8$ K) plasma (Koyama et al. 1986, 1989).

The right-hand axis in Figure 9 gives the source luminosity per decade of photon energy assuming a Galactic longitude extent of 1 rad and an effective distance of 3 kpc to the source region. This distance was calculated by taking the square root of the sum of the squares of the distances to various parts of the Galaxy weighted by their contribution to the measured flux according to Sacher & Schönfelder (1984), and then scaled by a factor 0.75 to account for a smaller scale of the Galaxy than they assumed. The Sacher & Schönfelder distribution is for the bremsstrahlung component only, so the effective distances may be different for the other components. One confirmation of this effective distance is that the low-energy cutoff of the X-ray emission observed by *SPARTAN 1* implies an absorption column density of $N_H = 4 \times 10^{21}$ cm^{-2} (Kawai et al. 1988), which is more consistent with 3 kpc than the 7.5 kpc to the Galactic center.

The luminosities calculated in this way for a diffuse emission are more uncertain than for a point source and are also not as easy to interpret. To estimate the actual total luminosity from the Galaxy for this emission, one should multiply the numbers derived from Figure 9 by a factor of 2–4 since the observed emission is mostly from our region of the Galactic disk. The numbers are useful, however, for comparing to other diffuse emissions and for estimating energetics. The total luminosity from keV to GeV energies is $\sim 10^{38}$ ergs s^{-1}, which is a modest energy compared with the total luminosity from the Galaxy of $\sim 3 \times 10^{43}$ ergs s^{-1}. More interesting are comparisons with other diffuse emissions from the Galactic disk. The total energy flux for the X-ray/gamma-ray Galactic ridge is $\sim 10^{-7}$ ergs cm^{-2} s^{-1}, which is significantly smaller than the $\sim 10^{-4}$ ergs cm^{-2} s^{-1} (Allen 1973) from the visible stars in the Milky Way, but larger than the $\sim 10^{-9}$ ergs cm^{-2} s^{-1} (Allen 1973) from the diffuse Galactic radio flux.

5. FUTURE OBSERVATIONS

In conclusion, we note that with *Granat* and the *Compton Observatory* now in orbit, intense observations are underway of both Galactic center point sources and the diffuse Galactic emission. For the point sources, *Granat* has already given us the first good sample of Galactic center point-source images, and the *Compton* instruments are providing a sensitive, multiyear study. However, neither of these missions gives continuous monitoring of the Galactic center and plane. With the short time-scale variability we see in 1E 1740.7−2942 and most other sources in the region, a dedicated monitoring mission is needed to fully study the region.

For the diffuse emission, the *Compton Observatory* will be able to make broad-band (50 keV–30 GeV) detailed measurements. Below ~ 1 MeV, it will be necessary to use *Granat* and OSSE scan data to subtract point source contributions. The diffuse flux is, for example, a strong signal for OSSE giving 60 σ detections at 100 keV (Tueller et al. 1992). The COMPTEL and EGRET instruments on *Compton* are mapping out the entire Galaxy between 1 MeV and 30 GeV. In the X-ray band, future observations of the Galactic ridge will be made by *ASTRO D* and XTE. Existing data sets may be able to further constrain the extent of the emission and its spectrum.

We thank D. Smith and M. Briggs for pointing out the importance of the *HEAO* A-4 observation, and L. Peterson and D. Gruber for information about the observation. We greatly appreciate discussions with A. Bazzano, J. Grindlay, R. Mushotzky, T. Prince, R. Ramaty, G. Ricker, J. Skibo, and P. Ubertini. We thank J. Grindlay for his 1989 May data point on 1E 1740.7−2942. We are grateful to the referee for calling our attention to the low *HEAO 3* 1980.2 continuum at 1 MeV and for other useful suggestions. We thank K. Pollock for assistance in the data analysis and in the preparation of this manuscript.

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