OSSE OBSERVATIONS OF THE SOFT GAMMA-RAY CONTINUUM FROM THE GALACTIC PLANE AT LONGITUDE 95°

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ABSTRACT

We present the results of OSSE observations of the soft gamma-ray continuum emission from the Galactic plane at longitude 95°. Emission is detected between 50 and 600 keV where the spectrum is fitted well by a power law with photon index $-2.6 \pm 0.3$ and flux $(4.0 \pm 0.5) \times 10^{-2}$ photons s$^{-1}$ cm$^{-2}$ rad$^{-1}$ MeV$^{-1}$ at 100 keV. This spectral shape in this range is similar to that found for the continuum emission from the inner Galaxy, but the amplitude is lower by a factor of 4. This emission is due to either unresolved and previously unknown point sources, or diffuse electron bremsstrahlung, or a combination of the two. Simultaneous observations with OSSE and smaller field-of-view instruments operating in the soft gamma-ray energy band, such as X-ray Timing Explorer or Beppo-SAX, would help resolve this issue. If it is primarily diffuse emission due to nonthermal electron bremsstrahlung, then the power in low-energy cosmic-ray electrons exceeds that of the nuclear component of the cosmic rays by an order of magnitude. This would have profound implications for the origin of cosmic rays and the energetics of the interstellar medium. Alternatively, if the emission is diffuse and thermal, then there must be a component of the interstellar medium at temperatures $\sim 10^9$ K.

1. INTRODUCTION

The Galactic plane is an extended source of gamma radiation. This has been demonstrated at energies above about 70 MeV with SAS-2 (Fichtel et al. 1975; Hartman et al. 1979), COS-B (Mayer-Hasselwander et al. 1982; Strong et al. 1988), and most recently with EGRET on the Compton Gamma Ray Observatory (CGRO; Hunter et al. 1995, 1997). This high-energy emission is generally believed to result from cosmic-ray interactions with interstellar gas and radiation through the processes of electron bremsstrahlung, inverse Compton scattering, and pion production (see, e.g., Bloemen 1989; Bertsch et al. 1993). Observations made with COMPTEL on CGRO (Bloemen et al. 1993; Strong et al. 1994, 1995, 1996) have confirmed that this Galactic plane emission extends down to energies near 1 MeV. Whereas there is no proof that this emission is genuinely diffuse and not the superposition of unresolved point sources, the spectrum of this emission from the Galactic center direction is a smooth extrapolation down to 1 MeV of the continua measured with SAS-2, COS-B, and EGRET that are fitted adequately with diffuse emission models.

The diffuse Galactic soft gamma-ray continuum is currently not well determined below 1 MeV. This is because at these energies the Galactic continuum is complicated by the presence of a number of point sources, many of which are variable. This energy range is, however, a very interesting energy regime for continuum processes, for, below 1 MeV, the candidate radiation mechanisms (inverse Compton scattering, nonthermal bremsstrahlung from cosmic-ray electrons or thermal bremsstrahlung from Galactic ridge thin hot [$T \sim 10^8$ K] plasma) could, in principle, contribute in approximately equal amounts to the total emission.

Observations of the Galactic plane toward the Galactic center made with the OSSE instrument on CGRO display evidence for daily variability at energies $< 150$ keV (Ulmer et al. 1997). The inferred variability implies that a significant portion of the Galactic plane continuum measured with OSSE from this direction is from point-source emission. In another analysis of Galactic plane observations made with OSSE (Kurfess 1995; Purcell et al. 1996), it was found that, when the contribution from the prominent point sources monitored during simultaneous observations with SIGMA is subtracted from the Galactic center spectrum measured with OSSE, the diffuse emission is essentially identical to that measured from the Galactic plane at $l = 25°$. Furthermore, the residual source-subtracted spectrum of this emission changes from a photon index of $\Gamma \sim 2.7$ ($dN/dE \propto E^{-\Gamma}$) for energies below $\sim 200$ keV to $\Gamma \sim 1.7$ at higher energies (Purcell et al. 1996; Strong et al. 1994). Thus, the soft gamma-ray emission (below 200 keV) from the inner Galaxy is more intense than the extrapolation of the higher energy continuum with index $\Gamma \sim 1.7$ and has a roughly constant longitude distribution over the central region of the Galaxy when the prominent sources are removed.

This corroborates observations made with the low-energy gamma-ray experiment flown on HEAO-1 (Peterson et al. 1990), where it was shown that the $90–280$ keV continuum emission has a longitude distribution similar to that $\sim 100$ MeV. More recently, Gehrels et al. (1991) have shown that the low-energy ($30–200$ keV) spectrum of the Galactic center observed with the balloon-borne Ge spectrometer GRIS was at that time very nearly equal to the spectrum observed from $l = 335°$, after correcting the Galactic center spectrum for the
contributions from the point sources 1E 1740.7–2942 and GRS 1758–258. Furthermore, hard X-ray observations from the direction of the Galactic center with detectors of moderate fields of view (15°–30°) show that, even though the observed fluxes vary in time, they have a lower envelope that coincides with the observed flux from $l = 335^\circ$ (Gehrels & Tueller 1993). In addition, emission from the Galactic plane has been detected through gaps in the passive collimators of the SIGMA telescope with essentially the same spectrum as observed with the other instruments (Claret et al. 1995).

At X-ray energies, extended emission has been observed from the Galactic ridge with Ginga (Koyama et al. 1989; Yamasaki et al. 1996). The spectrum displays prominent 6.7 keV line emission from He-like Fe and a continuum that is fitted by a thermal bremsstrahlung with a hint of a high-energy tail around 10 keV. This emission is probably a mixture of thermal and nonthermal bremsstrahlung. Observations of the diffuse X-ray emission (2.5–22 keV) with ART-P on board Granat from a region a few degrees around the Galactic center show that the hard emission (6.5–22 keV) has a different morphology, being more extended along the Galactic disk than the soft X-ray emission (8.5–22 keV) (Markevitch, Sunyaev, & Pavlinsky 1993; Sunyaev, Markevitch, & Pavlinsky 1993).

Information on the gamma-ray spectrum from regions outside the central radian of the Galaxy is sparse because the overall intensity is much lower. In this Letter, we present the results of an analysis of OSSE observations of the Galactic plane at $\ell = 95^\circ$. This is a direction nearly tangent to the solar circle where there are few cataloged hard X-ray sources. We find that the continuum below 200 keV has the same general spectral characteristics as observed by OSSE from the inner Galaxy, although it is reduced in intensity by a factor of 4. The spectrum below $\sim 600$ keV is adequately fitted by a power law with photon index $-2.6 \pm 0.3$. At this longitude, OSSE does not have sufficient sensitivity to detect the expected harder high energy component. If this emission is truly of diffuse origin and produced by cosmic rays interacting with ambient gas and radiation, then the spectrum and Galactic radial extent measured by OSSE impose severe energetic constraints on cosmic-ray origin scenarios.

2. OBSERVATIONS AND ANALYSIS

The Oriented Scintillation Spectrometer Experiment (OSSE) consists of four nearly identical Na(Tl)/Csl(Na) phoswich detectors operating in the 50 keV–10 MeV energy range. Each detector is passively collimated with a tungsten slat collimator defining an optical aperture (field of view) of $\sim 11.4 \times 3.8$ (FWHM) (see Johnson et al. 1993 for details).

Observations of the Galactic plane at longitude 95° were carried out in 1996 during viewing periods 515 (February 20–March 5) and 519 (April 23–May 7). The detector orientations at these times is shown in Figure 1. Each detector alternately observed the plane and background fields located $\pm 9^\circ$ (viewing period 515) and $\pm 12^\circ$ (viewing period 519) on alternating sides of the target field along the direction perpendicular to the long axis of the collimator (see Fig. 1). During viewing period 515, the detector orientation was such that the long axis of the collimator was nearly aligned with the Galactic plane, while in viewing period 519, it was inclined at 40°. The background-corrected spectra represent the excess of the two target fields over the corresponding background fields. Small corrections to these difference spectra for systematic scan-angle–dependent background effects were made.

The background-subtracted count rate at longitude 95° (viewing period 515) was about a factor of 4 lower than that obtained from OSSE measurements of the inner Galaxy. This can be compared with observations made at higher energies ($\sim 100$ MeV) with COS-B, where the flux level drops off by only a factor of 3 in going from the Galactic center to the solar tangent.

The background-subtracted count rate summed over all four detectors in 1 day time intervals from each of the viewing periods separately showed no evidence for variability within either observation period. The 50–150 keV count rates were $3.2 \pm 0.3$ counts s$^{-1}$ MeV$^{-1}$ for viewing period 515 and $1.7 \pm 0.3$ counts s$^{-1}$ MeV$^{-1}$ for viewing period 519. This is a difference of about 3.5 $\sigma$ and is consistent with that expected from the reduced exposure to the plane during viewing period 519 and the fact that the background fields for viewing period 519 partially overlap the plane (see Fig. 1). For a linelike source in the plane with negligible latitude extent ($\pm 1^\circ$), the measured flux in viewing period 519 would be approximately 50% that of viewing period 515. This fraction increases to about 70% if a wider latitude distribution ($\approx 5^\circ$ Gaussian FWHM) is assumed. From the measured count rates, this fraction is determined to be 0.54 $\pm 0.11$. This value places a 2 $\sigma$ upper limit of FWHM $\approx 8^\circ$.

To convert from flux through the OSSE collimator to flux per radian, it was necessary to assume a spatial distribution for the emission. We assumed that the longitude distribution at longitudes ($85^\circ$–105°) is roughly constant over the OSSE field of view. This is as expected for diffuse emission based on the $\gtrsim 30$ MeV EGRET observations (Hunter et al. 1997). Furthermore, we assumed that the distribution has the same latitude extent as that measured with OSSE from the inner Galaxy, where the distribution is fitted well by a Gaussian with FWHM $\approx 5^\circ$ (Purcell et al. 1996). We acknowledge that the true latitude distribution cannot be determined from our data, which provide only the 2 $\sigma$ upper limit of 8°. If, for example, FWHM $\approx 1^\circ$, then the flux per radian would be lower by a
The spectra from each viewing period are adequately fitted by single power-law models of spectral index $-2.7 \pm 0.3$ and $-2.3 \pm 0.6$ for viewing periods 515 and 519, respectively. Within the errors, these are consistent. To combine the data from both viewing periods, we scale the count rate of viewing period 519 by a factor that renders the 50–150 keV count rates of both viewing periods identical. This compensates for the different collimator orientations. These corrections are valid only up to 600 keV, where the data become statistically uncertain. Above that energy, where the current observations are marginally significant, the OSSE collimator response must be modeled more carefully.

We find that the spectrum over the range 50–600 keV in the combined data is fitted well by a single power law, $\Phi(E) = \frac{A(E/0.1 \text{ MeV})^{-\gamma}}{E}$, where $A = (4.0 \pm 0.5) \times 10^{-7}$ photons s$^{-1}$ cm$^{-2}$ rad$^{-1}$ MeV$^{-1}$ and $\Gamma = 2.6 \pm 0.3$. The reduced $\chi^2$ for 88 degrees of freedom is 1.15, which corresponds to a probability of 0.15. In Figure 2, we show this fit with the data.

Other spectral models, such as a broken power law or thermal Comptonization plus power law, cannot be ruled out, but they do not provide significantly improved fits. Fitting to a single power law restricted to energies below 200 keV results in a spectral index $\Gamma = 2.7 \pm 0.3$. The fit obtained using a broken power law has a break near 200 keV but is identical within errors below the break to that of the single power law shown in Figure 2. The spectral index above the break is harder but not well constrained. It is in accord with the spectrum measured with OSSE from the inner Galaxy (Kurfess 1995; Purcell et al. 1996).

An acceptable fit is also obtained with an optically thick thermal Comptonization (Sunyaev & Titarchuk 1980) plus power-law model. The Sunyaev-Titarchuk component required to account for the $\approx 200$ keV emission has temperature in the range 10–30 keV and a Thomson depth that is not very well constrained. The high-energy power law is hard ($\Gamma \approx -2$) but not meaningful owing to the limited statistical significance of the data above 200 keV. Such a model might represent the emission from an X-ray binary or distribution of such sources with thermal Comptonization spectra superposed on a background diffuse power-law component.

3. ORIGINS AND IMPLICATIONS

The central question concerning the origin of this soft gamma-ray emission is whether it is primarily diffuse or if it is greatly affected by one or more compact sources. There are two candidate hard X-ray point sources, the eclipsing LMXB 4U 2129+47 located at $l = 91\degree58, b = -3\degree04$ (Thorstensen et al. 1979; Ulmer et al. 1980; Garcia 1994) and the X-ray pulsar Cep X-4 at $l = 99\degree08, b = 3\degree78$ (Ulmer et al. 1973; Koyama et al. 1991). As can be seen from Figure 1, the detectors were more sensitive to both of these sources during viewing period 519. Hence, if either of these sources were substantial contributors to the observed OSSE flux, then the flux observed in viewing period 519 would have exceeded that observed in viewing period 515 in the absence of source variability. However, the 50–150 keV count rate in viewing period 519 was found to be $54\% \pm 11\%$ that of viewing period 515, more in accord with the emission being distributed along the Galactic plane.

In the range 50–150 keV, the OSSE collimator is fairly well represented by a $3\times11\degree4$ FWHM triangular response function. In viewing period 515, only 4U 2129+47 was in the detector field of view and only at the 7% response level; hence, we rule out Cep X-4 as a potential contributor to the viewing period 515 flux. In viewing period 519, 4U 2129+47 was in the field of view at the 54% level. We estimate the maximum contribution of 4U 2129+47 to the viewing period 515 flux in the 50–150 keV band. Assuming a latitude extent of 5° for the diffuse emission, the ratio of the response to the plane in viewing period 519 to that of viewing period 515 is 69%. From these numbers, a 2 $\sigma$ upper limit of 2% can be placed on the fraction of the 50–150 keV emission contributed by 4U 2129+47 in viewing period 515. Even if we make the unlikely assumption that thediffuse emission has negligible latitude extent ($\approx 1\degree$), then the ratio of the response to the plane in viewing period 519 to that of viewing period 515 is 52%, which allows for a 2 $\sigma$ upper limit of 3% for the contribution of 4U 2129+47 in viewing period 515.

Of course, suitably arranged time variability can be construed to yield an even greater contribution from 4U 2129+47. However, because each observation separately showed no evidence for day-to-day variability, this scenario seems unlikely. In addition, if 4U 2129+47 was responsible for the viewing period 515 emission, then its intrinsic flux corrected for the collimator response would be approximately 100 mCrab, an order of magnitude higher than the observed OSSE flux in viewing period 515. In this case, it would have been detected with BATSE on CGRO. In summary, although the ratio of the 50–150 keV count rate measured in viewing period 515 to that in viewing period 519 is consistent with the emission coming solely from the plane, we cannot rule out that 3% (2 $\sigma$ upper limit) is due to 4U 2129+47. Furthermore, we cannot rule out that the observed fluxes are due to other previously undetected hard X-ray sources. For the observed fluxes to be produced by a single source of constant intensity, it is constrained to lie in the darkly shaded region of Figure 1 and be at least 10 mCrab intensity in the 50–150 keV band. A source at this low intensity would not have been detected by BATSE over the duration of the OSSE observation.

Another possibility is that this emission arises from supernova remnants (SNRs). Recent X-ray observations with ASCA of the supernova remnant SN 1006 reveal intense nonthermal X-ray emission arising from the edges of the remnant shell (Koyama et al. 1995). This has been interpreted as synchrotron emission from $\approx 100$ TeV electrons accelerated by the first-order Fermi mechanism in the blast wave shock (Reynolds 1996). In fact, a nonthermal tail has been observed with OSSE from the supernova remnant Cas A (The et al. 1995). There were two SNRs in the fields of view of the Galactic plane $l =$
95° pointing, CTB 104A and 3C 434.1, neither of which has been detected at X-ray energies (Green 1995).

If, on the other hand, this emission is genuinely of a diffuse origin, then it could either be bremsstrahlung from low-energy (∼1 MeV) cosmic-ray electrons or inverse Compton emission from high-energy electrons. Compton up-scattering of photons from the cosmic microwave background, ambient infrared and starlight photons to energies ~100 keV requires electrons of energy in the range 100 MeV–10 GeV. Electrons at these energies are responsible for producing the Galactic synchrotron radio emission at frequencies ~100 MHz (see, e.g., Berezinskii et al. 1990, p. 191). However, the radio spectrum is observed to steepen above ~100 MHz. This is not in accord with OSSE observations of the inner Galaxy, which display the break in the opposite sense.

For these reasons, we next consider bremsstrahlung as a more likely mechanism. There is a problem, however, with the bremsstrahlung interpretation. Bremsstrahlung of ∼1 MeV electrons is energetically highly inefficient. The energy loss rate due to ionization and Coulomb collisions with the ambient plasma is several thousand times greater than the loss rate due to bremsstrahlung. On the Galactic scale, a large power is required to maintain these sub-MeV cosmic-ray electrons against energy losses to the interstellar medium. Since these electrons do not escape the Galactic disk, the Galaxy acts as a sort of calorimeter (Pohl 1993). The Galactic soft gamma-ray continuum luminosity is estimated to be ~10^{38} erg s^{-1} (Skibo, Ramaty, & Purcell 1995, 1996) from OSSE measurements of the inner Galaxy (Purcell et al. 1996). Therefore, more than 10^{18} erg s^{-1} must be supplied to the electrons producing this radiation (Chi & Wolfendale 1991; Skibo & Ramaty 1993; Skibo et al. 1995, 1996). This exceeds by an approximately order of magnitude the power supplied to the nuclear component of the cosmic rays (see, e.g., Berezinskii et al. 1990, p. 191). Furthermore, it is approaching the total power supplied by supernovae, the traditional sources of Galactic cosmic rays (∼10^{23} ergs s^{-1} assuming 10^{51} ergs every 30 yr). This large power is efficiently deposited into the ISM in the form of heat and ionization; thus, these electrons could be an important component. For example, they could provide some of the required 10^{40} ergs s^{-1} in heat and ionization to maintain the warm (10^5 K) intercloud medium (Reynolds 1990; Skibo et al. 1995). However, if these electrons penetrate cold neutral clouds, then excessive molecular dissociation would occur (Skibo et al. 1995).

It has recently been shown (Schlickeiser 1996) that stochastic Fermi reacceleration by gyroresonant wave-particle interactions in the ISM can give rise to the steep electron spectrum as required by the gamma-ray observations. However, the total power of ∼10^{40} ergs s^{-1} must still be supplied to the electrons through hydrodynamic turbulence. Whether such power is available in this form is an open question.

If, on the other hand, the emission is thermal bremsstrahlung from hot thin interstellar plasma, then the power required is simply that which is radiated, ~10^{36} ergs s^{-1}. This is far less demanding energetically, but it implies temperatures ~10^9 K. It is not clear whether gas in the ISM can be maintained at these temperatures, but detailed modeling of the ISM with such a superhot component is beyond the scope of this work.

4. SUMMARY

Gamma-ray continuum emission has been detected between 50 and 600 keV with the OSSE instrument on CGRO from the Galactic plane at longitude 95°. The spectrum is fitted well by a power law with photon index −2.6 ± 0.3 and flux (4.0 ± 0.5) × 10^{-2} photons s^{-1} cm^{-2} rad^{-1} MeV^{-1} at 100 keV. This spectrum is consistent with that of the soft gamma-ray component of the diffuse continuum emission from the inner Galaxy but is lower by approximately a factor of 4 in intensity. We conclude that either this emission is due to unresolved and previously unknown point sources, or it is diffuse electron bremsstrahlung, or it is a combination of the two. To resolve this issue, simultaneous observations with OSSE and smaller field-of-view instruments operating in the soft gamma-ray energy band, such as the X-ray Timing Explorer (XTE) or Beppo-SAX. If the emission is nonthermal bremsstrahlung, then a very large power is required, whereas a thermal bremsstrahlung interpretation requires temperatures ~10^9 K.

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