N92-21934

GRIS Observations of the Galactic Center and the Gamma-Ray Galactic Diffuse Continuum

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ABSTRACT

On two flights in 1988, the Gamma-Ray Imaging Spectrometer (GRIS) discovered the Galactic Center in a high state (>1 x 10^{-3} ph cm^{-2} s^{-1}) of positron annihilation line emission (511 keV) after nearly a decade of failed attempts to confirm the exciting early results of balloon and satellite instruments. These two flights represented the first flights of a new generation of high resolution germanium spectrometers designed to achieve significantly greater sensitivity for astrophysical observations. During the fall flight, an observation of the galactic plane at 335° longitude was also performed. This observation showed a very low level of 511 keV emission (2±1 x 10^{-4} ph cm^{-2} s^{-1}), confirming the Galactic Center origin of the line, and a high level of hard x-ray and gamma-ray continuum emission (1 x 10^{-4} ph cm^{-2} s^{-1} keV^{-1} at 100 keV), which we attribute to galactic diffuse emission. Improved fits to the spectrum of the Galactic Center are presented with the proposed diffuse component subtracted. We conclude that our Galactic Center continuum spectrum is consistent with the sum of the 1E1740.7-2942 spectrum observed by SIGMA/GRANAT and our l=335° galactic plane spectrum. The predicted diffuse flux should be easily measurable by the OSSE experiment on GRO.

INTRODUCTION

The Galactic Center region has been known to be a source of 511 keV gamma rays from positron annihilation since the 1970's, but the nature of this source was poorly understood. The line was first observed in 1970 by a balloon instrument (Johnson, Harnden & Haymes 1972), but was not convincingly identified as positron annihilation radiation until the high resolution germanium detector measurements of Leventhal, MacCallum & Stang (1978) in 1977, also a balloon instrument. The germanium spectrometer on HEAO-3 observed the source twice (Riegler *et al.* 1981), once in 1979 and again in 1980, and detected a significant decrease in the source intensity, which was subsequently confirmed by balloon measurements (Leventhal *et al.* 1982, 1986; Paciesas *et al.* 1982). At the same time, measurements by a very broad field-of-view (~130°) moderate resolution instrument on SMM showed a strong line with little variability (Share *et al.* 1990). To explain this discrepancy, Lingenfelter & Ramaty (1989) proposed a two component model with a variable point source near the Center and a diffuse line source to explain the excess observed by SMM.

In 1988, as part of a major campaign to observe Supernova 1987A (Tueller *et al.* 1990), the first two flights of the new GRIS instrument also observed the Galactic Center, which is conveniently separated by ~12 hours in Right Ascension from SN1987A. GRIS discovered that the annihilation line from the Galactic Center had returned to the high state observed by instruments in the 1970's. The difference in line flux between the Spring and Fall measurements indicated a statistically significant variability. In the Fall 1988 measurement, the line was observed to be significantly broadened, providing the first unambiguous evidence that the line is not narrow. We were very fortunate to get a long flight (>40 hours) in the Fall, that allowed a second pass on the galactic plane. We used this opportunity to make an observation of the plane at a galactic longitude l=335° and observed a very low 511 keV flux, confirming that the source was strongly concentrated toward the Galactic Center and placing significant new constraints on diffuse 511 keV line emission. These Galactic Center results from the GRIS balloon flights are published (Leventhal *et al.* 1989 and Gehrels *et al.* 1991), but in this paper we are presenting a more complete analysis of the continuum, including all the data from 25 keV to 8 MeV and with slightly improved data analysis procedures. These results are generally consistent with our previous publications.

In the Spring of 1990, an instrument similar to GRIS (HEXAGONE) observed the Galactic Center 511 keV line confirming the return of this source to a high state and providing more evidence for variability (Chapuis *et al.* 1991). Since the GRIS observations, the SIGMA experiment on GRANAT (a coded aperture imaging instrument) has provided exciting new information, including a possible identification of the variable point source of positrons. The strongest hard x-ray source in the Galactic Center region is usually 1E1740.7-2942. Because of the remarkable similarity of the spectrum of the Einstein source and CYG X-1, it has been suggested that the Einstein source is a black hole (Skinner *et al.* 1987; Cook *et al.* 1991). SIGMA observed a broad transient feature near 511 keV (~200 keV FWHM; <1 day; ~400 keV peak energy) from this source which may be associated with the production of positrons (Paul *et al.* 1991). Very recently, this source has also been observed by SIGMA in a low state where it is much weaker than the other Galactic Center hard x-ray sources (Sunyaev *et al.* 1991). The imaging observations raise an important question about the interpretation of the spectra from the earlier observations: how many and which sources are contributing to the observed spectra? In particular, the sum of the sources observed in the imaging instruments falls below the GRIS total spectrum by about a factor of two (Gehrels *et al.* 1991).

OBSERVATIONS AND DATA ANALYSIS

The GRIS instrument is a balloon-borne high resolution gamma-ray spectrometer which operates in the energy range 20 keV to 8 MeV (Tueller *et al.* 1988). It is one of a new generation of instruments that use arrays of cooled germanium detectors and heavy active shielding to achieve high sensitivity ($<2 \times 10^{-4}$ ph cm^{-2} s^{-1} 3σ narrow line upper limits for E>100 keV) and fine energy resolution (~2keV at 1 MeV). The field-of-view of the active collimator is ~17° at relevant energies. The Galactic Center was observed twice for ~12 hours in both the Spring (May 1) and Fall (Oct. 29) of 1988. A similar observation of the galactic plane at a longitude of l=335° was made in the Fall a day later. Alternate 20 minute pointings, on-source and off-source (background), were accumulated and the difference (source-background) was used to calculate the source flux. For more information on the observing program see Gehrels *et al.* 1991 and for the data analysis procedures see Tueller *et al.* 1990 and Barthelmy *et al.* 1991.

The data analysis procedures used here have minor improvements over those used in our previous publication (Gehrels *et al.* 1991). The procedures have been altered to perform the sum over energy for large continuum energy bins before calculating source minus background in each interval. This allows us to use directly determined statistical weights in calculating the average over observing intervals, even at the highest energies where the statistics are poor. Using this technique, we have extended our analysis to 8 MeV. Data in the energy range 25 to 35 keV, which was excluded from the previous analysis, has been included here. Finer energy bins are used for the continuum fit to provide for a better comparison of different models. Forward folding least-squares fits using the full detector response matrix including atmospheric corrections have been performed on a variety of models. The results of these fits, for the same models used in Gehrels *et al.* 1991, are essentially identical to the previous publication.

RESULTS

In our original analysis of the GRIS galactic plane observation, we were struck by the unexpectedly high level of hard x-ray continuum observed (roughly half the level observed from the Galactic Center). We had also noted a significant discrepancy between the sum of the hard x-ray point source spectra from imaging instruments (GRIP and SIGMA) and our Galactic Center continuum (also roughly a factor of two). Since the coded aperture imaging instruments are relatively insensitive to diffuse emission, this suggested a possible model to explain both results. Perhaps our galactic plane spectrum is truly diffuse emission from the plane, which extended to the Galactic Center and explains the discrepancy with the imaging instruments. Another anomaly in our fits to the galactic plane spectrum was the high level of the positronium tail observed on the positron annihilation line. (The best fit was an unphysical 121±8 %.) We have performed fits to some more complex models to help quantify and clarify these issues.

Table 1 and figure 3 show the results of a fit to the galactic plane spectrum with a broken power law plus a 511 keV line with positronium tail. The line is of 2σ significance only and does not appear at the correct energy, but there is a slightly higher minimum in χ^2 at 511 keV. The best fit to a broken power law includes no positronium continuum, but the data are consistent at the 1σ level with 100 % positronium. The introduction of a break is statistically significant, reducing χ^2_{min} from 39 for 38 degrees of freedom to 32 for 36 d.o.f. With the introduction of a break in the continuum spectrum the evidence for a 511 keV line in our galactic plane data is not compelling and should be interpreted as an upper limit.

Assuming this spectrum reflects diffuse emission from the plane, we have used a Comptonized disk model with 511 keV line and tail plus a fixed galactic plane model to perform fits to our Galactic Center spectra from the Spring and Fall of 1988. The results of these fits are given in table 1 and figures 2 and 4. The galactic plane 511 line (using the higher minimum at 511 keV) was included in the model and this explains the differences in the line parameters derived here from those in our previous publication. These differences should be considered as reflecting the possible systematic error in our Galactic Center 511 keV line measurement due to the uncertain level of contribution from a diffuse 511 keV line, but if we choose to fit the narrow line component as a free parameter, the resulting best fit is nearly identical to table 1 for Fall 1988. The 511 keV line profile shown in figure 1 is essentially the same as in our previous publication. Using a larger set of models, it was possible to find fits to our Galactic Center continuum spectra consistent at the 2σ level with no positronium tail on the 511 keV line. This is a minor discrepancy with our previously reported results and illustrates the sensitivity of positronium fraction determination to the underlying continuum model. In both cases a good fit to the

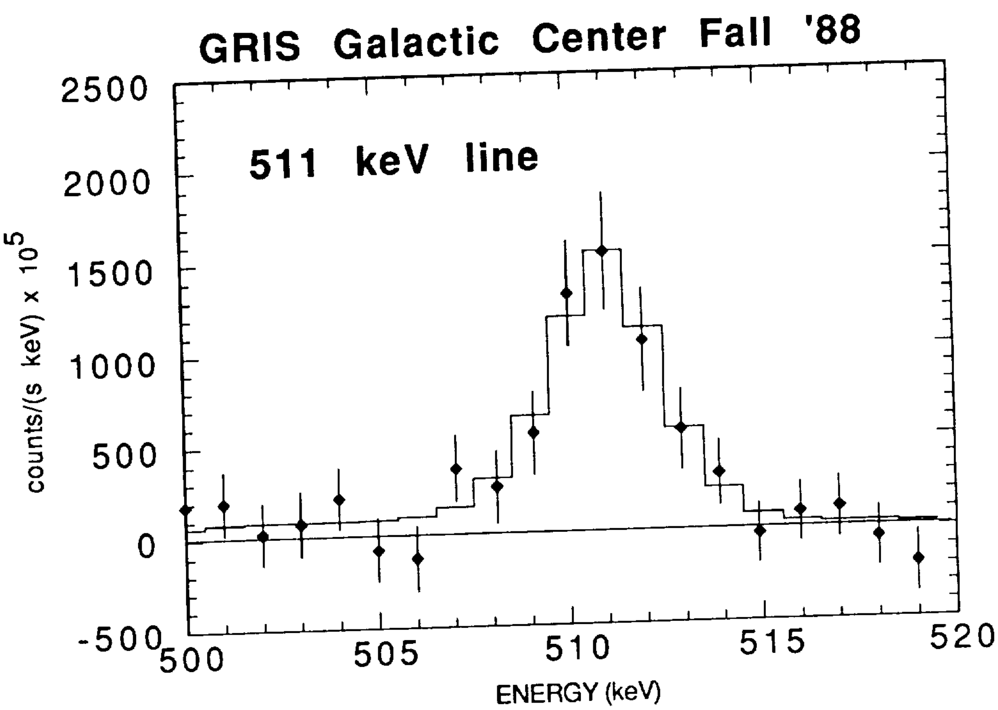

Figure 1 Galactic Center positron annihilation line and binned model (solid line).

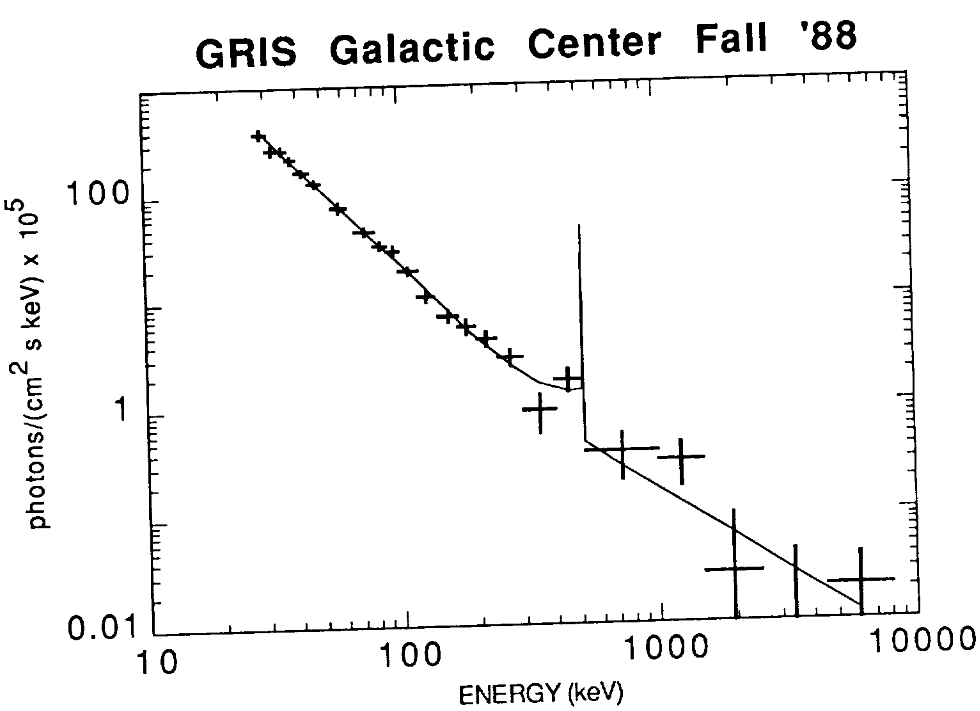

Figure 2 Galactic Center continuum data and fit (solid line).

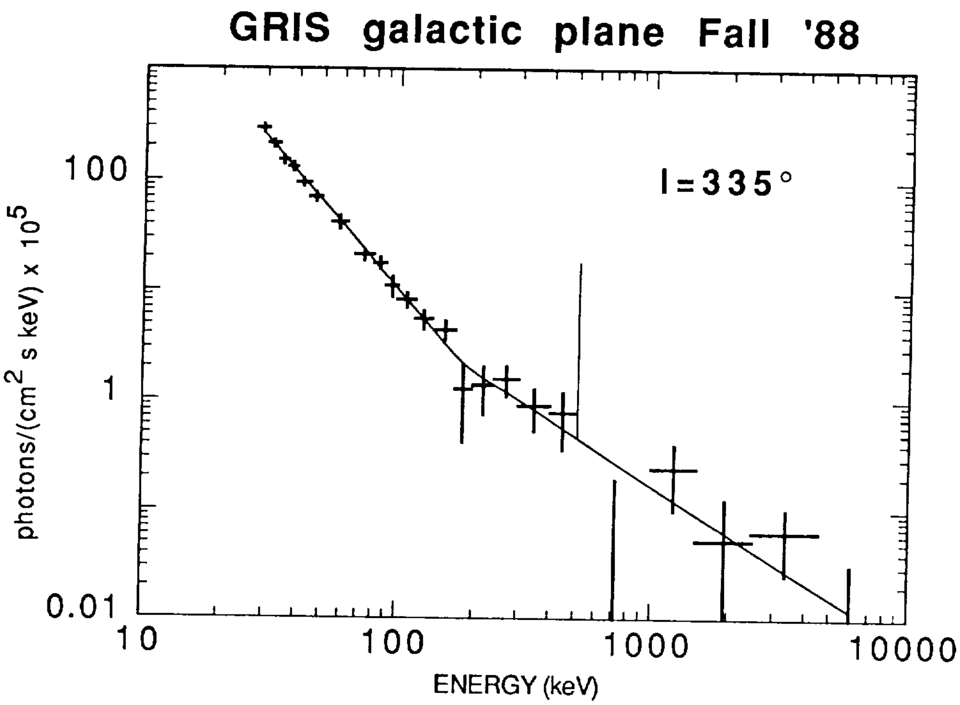

Figure 3 Galactic plane continuum data and fit (solid line).

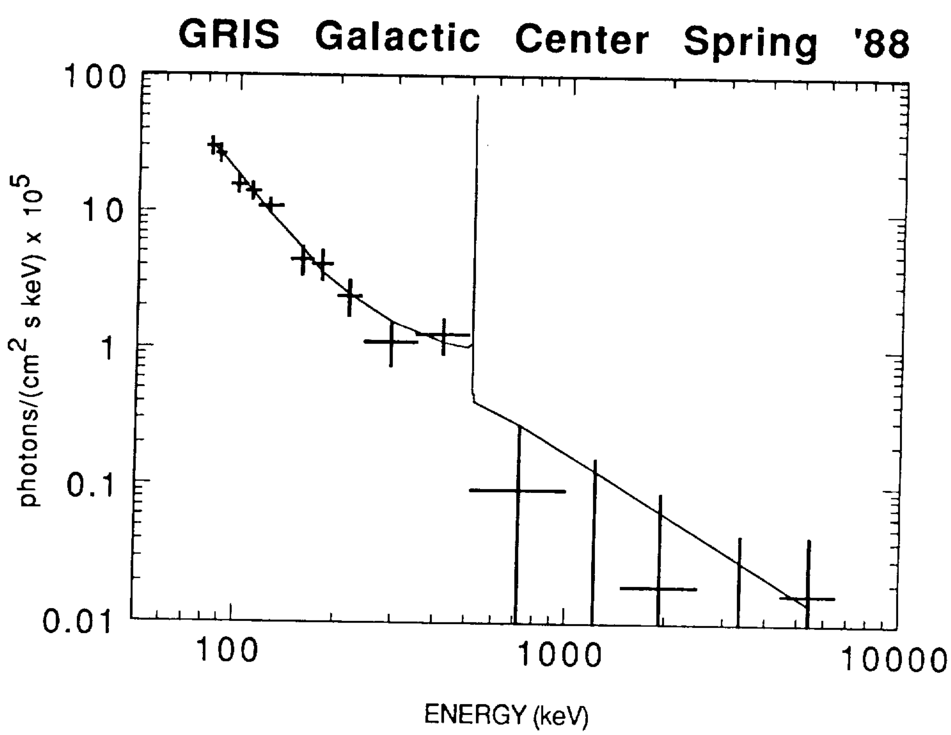

Figure 4 Galactic Center continuum data and fit (solid line).

TABLE 1 FIT RESULTS

galactic plane l=335°	Fall '88		Galactic Center - galactic plane model	Spring '88		Fall '88	
χ^2minimum	31.9	36 d.o.f.	χ^2minimum	36.9	30 d.o.f.	30.2	36 d.o.f.
flux at 100 keV (ph/(cm^2 s keV) x 10^5)	10.0	±0.5	flux at 100 keV (ph/(cm^2 s keV) x 10^5)	7.8	±0.9	11.3	±0.7
slope γ E < break	2.64	±0.06	electron temp KT (keV)	35	+13 -10	52	+25 -11
break energy (keV)	182	+34 -43	optical depth τ	2.7	+∞ -2.2	2.3	±0.6
slope γ E > break	1.47	+0.24 -0.17					
line flux (ph/(cm^2 s) x 10^5)	18	±8	line flux (ph/(cm^2 s) x 10^5)	54	±15	98	±15
peak energy (keV)	509	±0.4	peak energy (keV)	511.1	±0.7	511.0	±0.3
line FWHM (keV)	0	< 6	line FWHM (keV)	0	< 4	3.4	±0.8
positronium flux (ph/(cm^2 s) x 10^5)	0 to	80	positronium flux (ph/(cm^2 s) x 10^5)	157	±79	225	+84 -109
positronium fraction (%)	0 to	100	positronium fraction (%)	88	+19 -31	81	+14 -26

Galactic Center spectrum minus the galactic plane broken power law model can be achieved with a Comptonized disk model similar to that used by the SIGMA and GRIP teams to fit 1E1740.7-2942 (Sunyaev *et al.* 1991; Cook *et al.* 1991). Note that the flux above the line is almost entirely due to the proposed diffuse component and does not show an MeV hump that was reported by HEAO 3 (Riegler *et al.* 1981).

DISCUSSION

We predict, by scaling our 2σ upper limit to the OSSE FOV (11°), that OSSE will see less than 2 x 10^{-4} ph cm^{-2} s^{-1} of diffuse 511 keV emission from the galactic plane at 25° from the Center (see OSSE results in these proceedings). Taking all previous measurements into account, we predict that OSSE will observe variable levels of 511 keV line emission from the Galactic Center. We propose, as a model, that the GRIS galactic plane spectrum at l=335° is dominated by diffuse emission from our Galaxy which extends at least to the Galactic Center region. The GRIS Galactic Center continuum measurements are consistent with a model where the spectrum is dominated by this diffuse emission and a Comptonized disk spectrum from the 1E1740.7-2942 source (each roughly contributing equally). This model would also explain the discrepancy between the sum of the point source spectra observed by imaging instruments and the GRIS spectrum for the Galactic Center region. It is, of course, also possible to explain these results by invoking variable sources, such as the known hard x-ray transient source GX339-4, to explain our galactic plane spectrum. Similarly, there are many known transient sources in the Galactic Center region at could be used to explain any discrepancies between imaging and non-imaging spectra that were not measured simultaneously. A detailed comparison of other measurements of the Galactic Center spectrum and this model is presented in an accompanying paper in these proceedings (Gehrels and Tueller 1991). This paper shows that the measured Galactic Center spectrum has never been less than our proposed diffuse spectrum, but it has been identical to our spectrum in a few instances, presumably when all the point sources were turned off. This diffuse continuum emission would be easily detected by OSSE observations of the galactic plane as shown in figure 5 (60σ at 100 keV) and OSSE will provide a definitive test for our proposal.

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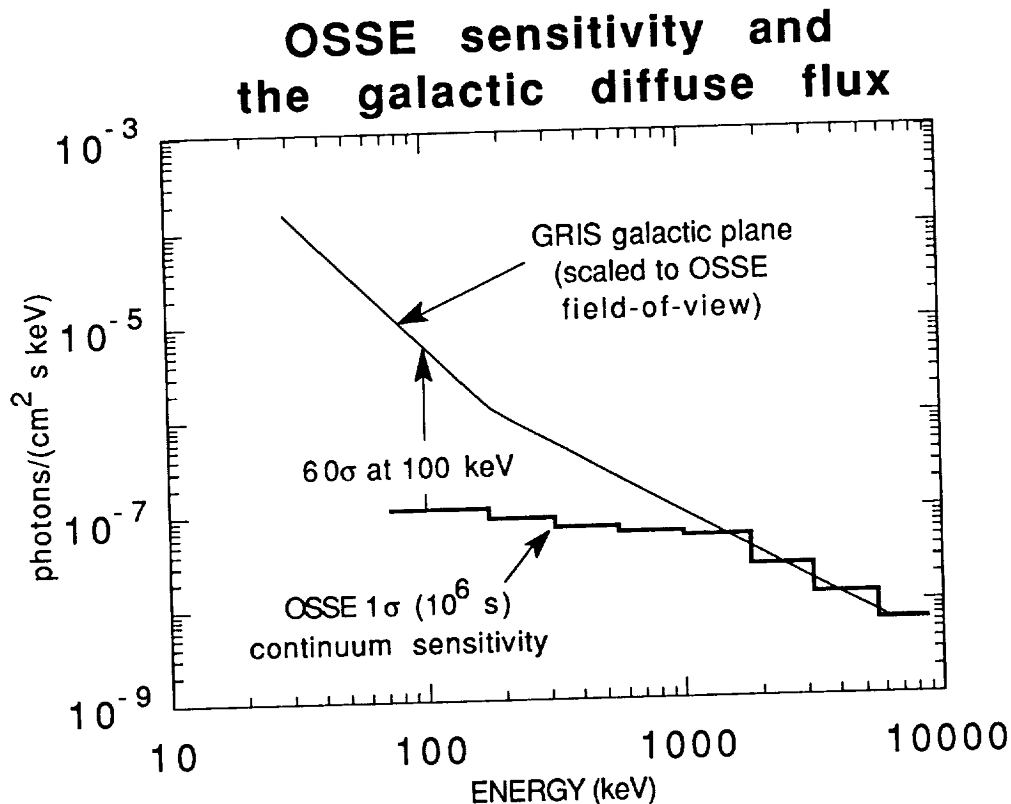

Figure 5 Proposed galactic diffuse component and the OSSE continuum sensitivity.

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