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GRIS OBSERVATIONS OF POSITRON ANNIHILATION RADIATION FROM THE GALACTIC CENTER

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ABSTRACT

We report new observations of the Galactic center positron annihilation source in which, for the first time, the 511 keV line has been spectrally resolved and the Galactic plane and center components have been independently measured. High-resolution spectra were obtained of the Galactic center with the Gamma-Ray Imaging Spectrometer (GRIS) during May and October of 1988 balloon flights. The 511 keV line source was found to be turned on again in October of 1988, at a flux of $(11.8 \pm 1.6) \times 10^{-4}$ photons cm^{-2} s^{-1}, after being observed in a quiescent state since the early 1980s. There is evidence for variability between May and October. An observation of a point in the Galactic plane 25° west of the center was made during the October flight. The 511 keV line flux for this pointing was significantly lower, less than 4.0×10^{-4} photons cm^{-2} s^{-1} ($2\ \sigma$ upper limit), than that for the center pointing, proving unambiguously that the center emission is concentrated near $l^{\text{II}} = 0°$. The GRIS data combined with that from other narrow-field observations in the 1980s support the two-component model of the positron annihilation source. The best fit to these data sets gives a flux of $\sim 8 \times 10^{-4}$ photons cm^{-2} s^{-1} for the center point source component in its high state. A strong hard X-ray continuum was detected in the Galactic plane observation. This "diffuse" continuum component makes up the difference between the observed continuum in the GRIS Galactic center pointing and the known point source contributions, solving the long-standing mystery of why wide-field instruments have detected such high continuum emission from the Galactic center.

Subject headings: galaxies: The Galaxy — gamma rays: general

1. INTRODUCTION

It has been known since the 1970s that the Galactic center region harbors a powerful positron source, but its location and nature have not been understood. The positrons annihilate with electrons in the source region to produce a spectral line at 511 keV and a continuum below the line due to either three-photon annihilation of a positronium atom (Leventhal 1973), Compton scattering in the source region (Forrest 1982; Bildsten & Zurek 1988), or gravitational redshifts of the line. The line was first detected in 1970 (Johnson, Harnden, & Haymes 1972), but it was not uniquely identified as positron annihilation radiation until the first high-resolution (germanium detector) observation in 1977 (Leventhal, MacCallum, & Stang 1978). To date, more than 20 observations have been made (see reference list in Lingenfelter & Ramaty 1989). During its high state in the 1970s, the positron source was detected at flux levels of 10^{-3} photons cm^{-2} s^{-1} or higher corresponding to luminosities of 7×10^{36} ergs s^{-1} or more in the narrow 511 keV line. The source decreased in intensity in 1980 (Riegler et al. 1981) and was not detected during observations in 1981 and 1984 (Leventhal et al. 1982, 1986; Paciesas et al. 1982). During this period, however, the wide field-of-view (130°) spectrometer on the *Solar Maximum Mission* (*SMM*) continued to detect a strong line from the region (Share et al. 1990). This has led to a two-component model for the source (Lingenfelter & Ramaty 1989): a variable point source located at or near the center and a steady state source distributed along the Galactic plane. Possible production mechanisms for the positrons are γ-γ interactions near a black hole for the point source component (Lingenfelter & Ramaty 1983) and β^+ decays of radionuclides generated in supernovae over the past $\sim 10^5$ yr for the distributed source (Signore & Vedrenne 1988; Clayton 1973). The point source identification may already be in hand. Recently, the SIGMA instrument on the *GRANAT* spacecraft has observed a variable spectral feature near 511 keV from 1E1740.7−2942, an object 0°.7 from the center (Paul et al. 1991). SIGMA also observed a strong, approximately steady hard X-ray continuum from this source (see also Skinner et al. 1987; Cook et al. 1991) and a weaker continuum from GRS 1758−258. These were the only two Galactic center γ-ray sources detected.

The case for the two-component model is strengthened considerably by the observations presented in this *Letter* made by the Gamma-Ray Imaging Spectrometer (GRIS) in 1988 May and October and by the new results from the FIGARO II experiment in 1988 November (Niel et al. 1990) and the HEXAGONE spectrometer in 1989 May (Chapuis et al. 1991). A preliminary analysis of the GRIS line data was reported by Leventhal et al. (1989).

2. OBSERVATIONS

The GRIS instrument (Tueller et al. 1988) is a balloon-borne high-resolution spectrometer operating in the 20 keV to 8 MeV

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energy range. It is a high-sensitivity instrument with a detector array consisting of seven of the world's largest high-purity n-type coaxial germanium crystals. The total active detector volume is ~ 1530 cm^3, and the total effective area at 511 keV is ~ 85 cm^2. A thick (15 cm) sodium iodide anticoincidence shield surrounds the detectors except for aperture holes which define the instrument's 18° FWHM (at 511 keV) field of view.

The energy calibration of the germanium detector signals is determined by linear interpolation between strong, narrow background lines at 198, 511 and 1461 keV (Tueller et al. 1990). The 511 keV calibration line is obtained from vetoed events in a special mode and is independent of the nonvetoed data used for the source analysis. The detector energy resolution was 1.8 keV FWHM at 511 keV for the October flight. The 511 keV background line is broadened by Doppler effects in the atmosphere to a width of 2.9 keV FWHM and has an intensity of 0.17 counts s^{-1}, which is ~ 3 times the strength of the 1988 October Galactic center line. An electronics problem, caused by saturating events due to charged particles, degraded the resolution in the maiden May flight to ~ 1%.

Observations of the Galactic center were made during flights on 1988 May 1 and 1988 October 29 and of a point in the Galactic plane 25° west of the center ($l^{\rm II} = 335°$, $b^{\rm II} = 0°$; chosen to exclude the center from the field of view) during the October flight. The flights were from Alice Springs, Australia, at mean atmospheric vertical depths of 4.7 and 6.0 g cm^{-2} for the May and October Galactic center observations and 4.5 g cm^{-2} for the Galactic plane. Except as noted below, observations were divided into 20 minute intervals alternating between target and background pointings. The backgrounds were taken at the same zenith angle as the target, but with the instrument rotated in azimuth to minimize the extent of the Galactic plane in the field of view and to exclude all known γ-ray sources. For the Galactic center observation (but not the Galactic plane observation), the instrument would have been pointed too near the zenith to take background as described above for ~ 100 minutes centered on the zenith meridian transit. During this period, two 50 minute background pointings were made on either side of a 100 minute target pointing. The total observing time (target plus background) used in the following analysis is 8.6 and 9.2 hours for the May and October Galactic center observations and 6.1 hours for the Galactic plane observation. The pointing and spectroscopic performance of the instrument were verified during each flight by observations of the Crab, which gave spectra consistent with previous measurements.

3. ANALYSIS AND RESULTS

Spectra from each detector were gain-corrected, compressed by a factor of ~ 4 into 1 keV bins, and summed together into a single composite spectrum for each analysis interval. Background intervals were subtracted from target intervals after scaling for live-time, and the difference was corrected to the mean slant-range atmospheric depth of the observation. These individual flux estimates were then averaged to obtain a final estimate and variance.

Model fits to the data were derived by multiplying a model photon spectrum by the instrument response matrix and adjusting parameters in the model to minimize χ-squared. The method for fitting and deriving error bars are described by Tueller et al. (1990). The response matrix has the effective area times the atmospheric attenuation convolved with the instrument resolution on the diagonal and terms for escape radiation and Compton scattering in the instrument and atmosphere off the diagonal. A Gaussian was used for the instrument resolution function for the October flight. For the May flight, the electronics problem caused a double-peak line shape which we modeled as two Gaussians and a rectangular fill function. The relative strength of the peaks and fill function were chosen as functions of energy to give good fits to the shapes of intrinsically narrow background lines between 198 and 1461 keV.

The model photon spectrum used to fit the data has three terms: (1) a power-law continuum of the form $A\,(E/100\ \mathrm{keV})^{-\alpha}$, (2) an orthopositronium three-photon continuum with an amplitude parameter $F_{3\gamma}$ (integral flux), and (3) a Gaussian line near 511 keV with parameters for line flux F_{511}, centroid energy E_{511}, and width W_{511} (FWHM). The parameters for the power-law continuum are determined primarily by the spectrum below ~ 300 keV. In other measurements (Riegler et al. 1985; Harris et al. 1990) the data above 511 keV were sufficiently different from the extrapolated low-energy power law to warrant inclusion of added terms in the model. The GRIS data in this energy range, however, are of low statistical significance and are consistent with the low-energy power law, so we have not included additional terms at this time (except in the systematic error estimations described below). In future work, other fits to the continuum just below the line will be studied, including terms for Compton scattering in the source region and gravitational redshifts of the line.

The data and model fits for the three GRIS observations are shown in Figure 1, with the energy bands near 511 keV expanded in Figure 2. The best-fit model parameters and statistical errors are listed in Table 1. Also listed are derived values for the positronium fraction (Brown & Leventhal 1987), which is defined as the fraction of positrons annihilating via the formation of a positronium atom, and is equal to $4F_{3\gamma}/(4.5F_{511} + 3F_{3\gamma})$.

Systematic errors in the 511 keV flux, not included in Table 1, were estimated by subtracting adjacent background intervals from each other and searching for residuals at 511 keV. No residual line flux was found above statistical errors, indicating that the systematic errors are at most equal to the statistical errors. Also, GRIS spectra of other sources without 511 keV lines show no distortion or features in this energy band. Systematic errors for the three-photon flux and positronium fraction were estimated by performing various types of fits to the data, including local fits to the continuum near 511 keV and fits to the full spectrum with a break in the power-law component. The local fits detect steps in the continuum at 511 keV due to the three-photon continuum and/or Compton scattering in the source. Compared with fits to the full continuum, they have poorer statistics but are less sensitive to uncertainties in the underlying continuum. For the full fits, we allowed a break (near 200 keV) in the slope of the power-law component to better match the data points above 511 keV (see Fig. 1). The results from this fitting for the three-photon continuum and positronium fraction are summarized in Table 1 by the systematic range of values. The large systematic ranges prevent detailed comparisons of the three measurements at this time, but do show that the positronium fraction is at least 50% for the Galactic center observations.

4. DISCUSSION

There is evidence in the GRIS data for variability of the 511 keV line flux on time scales of less than 6 months. The 1988

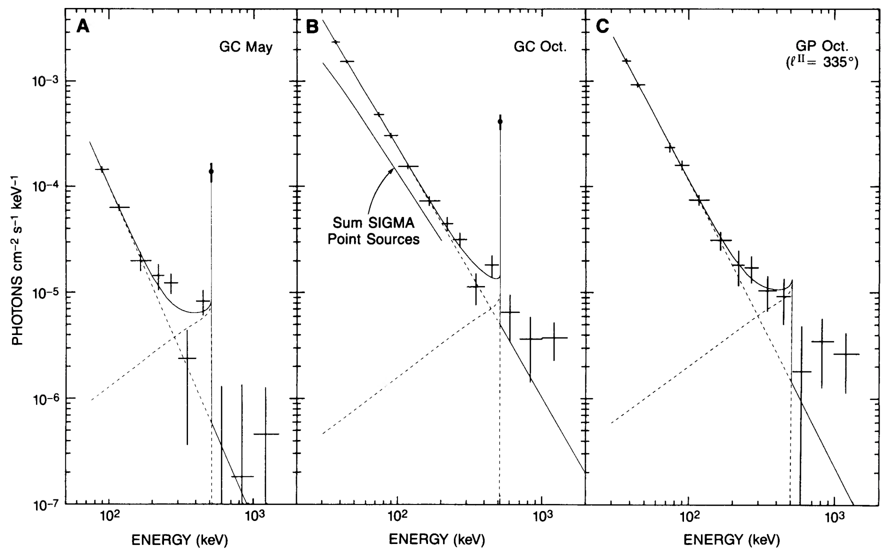

FIG. 1.—(*a–c*) Spectra and model fits for the 1988 GRIS observation of the Galactic center (GC) and Galactic plane (GP). Data between 52 and 68 keV have large statistical and systematic uncertainties due to the presence of strong background lines in this range and are not plotted. The sum of SIGMA point sources 1E1740.7−2942 and GRS 1758−258 in 1990 (Paul et al. 1991) are shown for comparison in (*b*)

May and October fluxes are inconsistent with a steady state mean value at the 95% confidence level. Another important and unique result is the low line flux for the Galactic plane pointing 25° away from the center. This is the first time the Galactic plane has been separately observed during a Galactic center high state and proves that the variable source is concentrated near the center. As we have recently shown (Gehrels 1991), the low flux value for this Galactic plane pointing is inconsistent at the 3.7 σ significance level with the CO-type models of the diffuse 511 keV line component used in the *SMM* analysis (Harris et al. 1990). The balloon data from 1981 through 1988 are more consistent with a diffuse component that has a relatively flat distribution over the central radian and a low flux value in the range (1.2–1.6) $\times 10^{-3}$ photons cm^{-2} s^{-1} rad^{-1} (Gehrels 1991; Ramaty 1991). For this model, the only 1980's balloon measurement with a strong, statistically significant point source component of the 511 keV line is the GRIS 1988 October observation at a value of $\sim 8 \times 10^{-4}$ photons cm^{-2} s^{-1}.

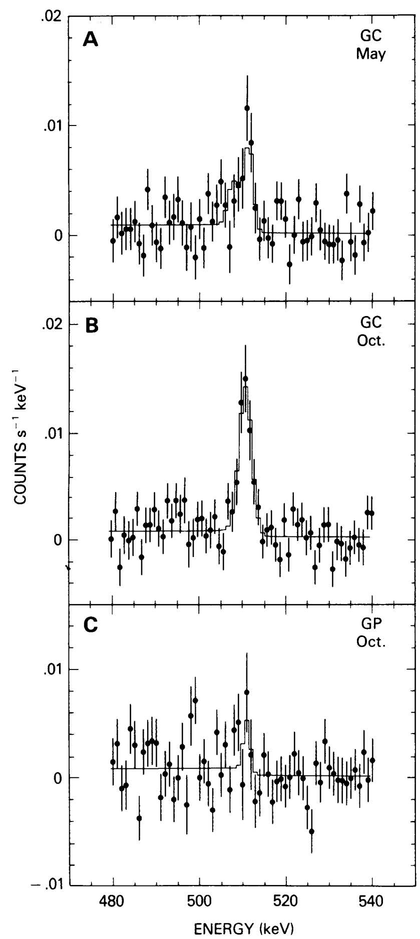

FIG. 2.—(*a–c*) Spectra and model fits in the vicinity of the 511 keV line for the 1988 GRIS observations.

The GRIS October observation is the first time the Galactic center 511 keV line has been spectroscopically resolved. In addition to the overall line width listed in Table 1, we have derived a width for the point source component of the line by fitting the data with a composite line made up of three Gaussians. Two of the Gaussians were for the assumed diffuse component and had fixed parameters (see Gehrels 1991 for specific parameters) derived from models of Guessoum, Ramaty, & Lingenfelter (1990), while the Gaussian for the point source component had free parameters determined by the best fit. The line width for the point source component was found to range from 2.7 to 3.6 keV depending on which regions of the interstellar medium the diffuse annihilation is assumed to take place. This width of ~ 3 keV implies a temperature for the point source annihilation region of $\sim 7 \times 10^4$ K if the width is due to thermal broadening or implies an orbit of $\sim 10^5$ Schwarzschild radii if the width is due to annihilation in a Keplerian ring around a black hole (Bhattacharya & Gehrels 1991).

A strong hard X-ray continuum is seen in Figure 1*c* for the 1988 October Galactic plane observation. We have found that the sum of this spectrum plus the continuum emission from point sources 1E1740.7−2942 and GRS 1758−258 observed by SIGMA in 1990 (Paul et al. 1991) precisely equals the

TABLE 1

MODEL FIT PARAMETERS FOR GRIS DATA

Parameter	1988 May Galactic Center	1988 October Galactic Center	1988 October Galactic Plane
F_{511} (photons cm^{-2} s^{-1})	$(7.5 \pm 1.7) \times 10^{-4}$	$(11.8 \pm 1.6) \times 10^{-4}$	$(1.8 \pm 1.1) \times 10^{-4}$ $<4.0 \times 10^{-4}$ (2 σ)
Centroid, E_{511} (keV)	511.46 (+0.33/−0.43)	510.97 (+0.22/−0.29)	511.0 fixed
Width, W_{511} (keV)	0 ± 2.4	2.9 ± 0.6	0 ± 3.6
Power-law A[a]	$(1.90 \pm 0.09) \times 10^{-4}$	$(2.28 \pm 0.06) \times 10^{-4}$	$(1.06 \pm 0.06) \times 10^{-4}$
Power-law α[a]	3.15 ± 0.25	2.36 ± 0.04	2.62 ± 0.08
$F_{3\gamma}$ (photons cm^{-2} s^{-1}):			
Best fit	$(3.3 \pm 0.8) \times 10^{-3}$	$(2.1 \pm 0.8) \times 10^{-3}$	$(2.6 \pm 0.7) \times 10^{-3}$
Positronium fraction (%):			
Best fit	99 ± 8	72 ± 13	121 ± 8
χ^2_{min}/d.o.f.	31/24	22/28	27/29
$F_{3\gamma}$ (photons cm^{-2} s^{-1}):			
Systematic range	$(1-3) \times 10^{-3}$	$(1.5-4.0) \times 10^{-3}$	$(0-4) \times 10^{-3}$
Positronium fraction (%):			
Systematic range[b]	56–100	57–96	0–>100

[a] Power law = $A(E/100 \text{ keV})^{-\alpha}$.

[b] Systematic range for positronium fraction includes $F_{3\gamma}$ systematic errors and F_{511} 1 σ statistical errors.

30–200 keV GRIS continuum spectrum from the Galactic center in 1988 October (Fig. 1*b*). We thus suggest, based on the assumption that the Galactic center point source spectra were similar in 1988 and 1990, that there is continuum emission from the Galactic plane with approximately constant intensity and spectrum over the central radian. The source may have a truly diffuse nature as for bremsstrahlung from cosmic-ray electrons or may be the combined emission from many weak hard X-ray point sources in the Galactic plane. For the October Galactic center observation at 100 keV, the "diffuse" component is 44% of the emission while the point sources 1E1740.7−2942 and GRS 1758−258 are 35% and 21%, respectively. It is interesting to note that the unusually low hard X-ray continuum emission below 150 keV observed by HEXAGONE in 1989 May (Matteson 1991) is equal to just the "diffuse" component in the instrument's 20° field of view. This suggests that 1E1740.7−2942 may have been in a very low state of hard X-ray emission at the time, lower than any seen by SIGMA (Paul et al. 1991) or GRIP (Cook et al. 1989).

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Noted added in proof.—The low hard X-ray state of 1E1740.7−2942 that we suggest for the 1989 HEXAGONE observation has indeed been seen by SIGMA in 1991 February and March (see R. Sunyaev et al., IAU Circs., 5204 and 5245).