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The Astrophysical Journal, 621:296–300, 2005 March 1
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INTEGRAL SPI LIMITS ON ELECTRON-POSITRON ANNIHILATION RADIATION FROM THE GALACTIC PLANE

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Received 2004 September 8; accepted 2004 October 15

ABSTRACT

The center of our Galaxy is a known strong source of electron-positron 511 keV annihilation radiation. Thus far, however, there have been no reliable detections of annihilation radiation outside of the central radian of our Galaxy. One of the primary objectives of the *INTEGRAL* (*International Gamma-Ray Astrophysics Laboratory*) mission, launched in 2002 October, is the detailed study of this radiation. The Spectrometer on *INTEGRAL* (SPI) is a high-resolution, coded-aperture gamma-ray telescope with an unprecedented combination of sensitivity, angular resolution, and energy resolution. We report results from the first 10 months of observation. During this period a significant fraction of the observing time was spent in or near the Galactic plane. No positive annihilation flux was detected outside of the central region ($|l| > 40°$) of our Galaxy. In this paper we describe the observations and data analysis methods and give limits on the 511 keV flux.

Subject heading: gamma rays: observations

Online material: color figure

1. INTRODUCTION

Electron-positron annihilation radiation from the central region of our Galaxy was first reported by balloon-borne instruments more than 30 years ago (Johnson et al. 1972; Johnson & Haymes 1973; Haymes et al. 1975). Since the first detection, there have been many balloon and satellite observations (Leventhal et al. 1978, 1980, 1993; Gehrels et al. 1991; Mahoney et al. 1994; Teegarden et al. 1996; Purcell et al. 1997). Both narrow-line 511 keV and continuum positronium emission have been observed (Leventhal et al. 1980; Purcell et al. 1997; Teegarden et al. 1996; Strong et al. 2003). Early measurements (Riegler et al. 1981; Paciesas et al. 1982; Leventhal et al. 1982, 1986) suggested that the annihilation radiation was time-variable. However, more extensive later observations showed no evidence of variability (Share et al. 1988; Gehrels et al. 1991; Leventhal et al. 1993; Mahoney et al. 1994; Teegarden et al. 1996; Purcell et al. 1997; Harris et al. 1998). The current consensus favors the latter conclusion. The most extensive results on the spatial distribution of the annihilation radiation prior to *INTEGRAL* came from the OSSE experiment on the *Compton Gamma Ray Observatory.* OSSE is a scintillator spectrometer with a simple $4° \times 11°$ collimator. Many scans were made through the central region of our Galaxy, although relatively few data were taken in the Galactic plane outside of this region. The OSSE data were well described by a two-component bulge distribution plus a somewhat less well-established disk component. One bulge model that gave a reasonable fit to the data consisted of a circularly symmetric Gaussian of FWHM $\sim 5°$ plus an elongated Gaussian with a width of $\sim 30°$ in longitude and $\sim 5°$ in latitude (Kinzer et al. 2001). Early OSSE papers discussed a possible positive latitude enhancement, the so-called annihilation fountain (Purcell et al. 1997). However, later analysis (Milne et al. 2001; Kinzer et al. 2001) found little or no evidence of such a feature.

Many different ideas have been advanced, but despite numerous observations over the past 30 yr, the origin of the Galactic positrons remains a mystery. Plausible scenarios include the following (see Casse et al. [2004] and references therein):

Nucleosynthesis in Massive Stars.—Wolf-Rayet (W-R) stars are massive stars with strong stellar winds. Radioactive elements created through hydrostatic nucleosynthesis in the cores of such stars can be convected to the surface and carried into the interstellar medium (ISM) by their stellar winds. Some of the radioactive elements will undergo β^+ decay, and the emitted positrons will annihilate in the ISM long before they can escape from the Galaxy.

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Fig. 1.—*INTEGRAL* SPI exposure map of the Galaxy for the first 10 months of operation of *INTEGRAL*. Horizontal range is 180° to −180°. Vertical range is −90° to 90°. A large fraction of the observations is concentrated in the Galactic plane. The characteristic "pinwheel" patterns in some regions are due to modulation of the light-bucket response by the SPI coded-aperture mask. Color bars are in units of seconds. [*See the electronic edition of the Journal for a color version of this figure.*]

Type Ia Supernovae.—Radioactive nuclei are created by explosive nucleosynthesis in Type Ia supernovae, some of which decay with positron emission. The positrons will annihilate in either the expanding shell or the surrounding ISM. The principal uncertainty is in the escape fraction of annihilation photons from the expanding shell.

Hypernovae.—A hypernova is an asymmetric explosion of a W-R star. Positrons can be efficiently transported outward by strong jets and escape into low optical depth regions, where they subsequently annihilate.

Black Holes and Pulsars.—Electron-positron pair production is believed to occur in black hole jets and pulsar magnetospheres.

Cosmic-Ray Interactions.—Cosmic rays colliding with nuclei in the ISM can produce π^+[17] or excitation followed by β^+ decay.

Dark Matter.—There has been recent speculation about the possible existence of light ($m < 100$ MeV) dark matter particles that would decay or annihilate primarily through the formation of electrons and positrons. Dark matter decay or annihilation could possibly account for the bulge component of the electron-positron annihilation radiation.

2. OBSERVATIONS

The Spectrometer on *INTEGRAL* (SPI) is a coded-aperture telescope using an array of 19 cooled germanium detectors for high-resolution spectroscopy (Vedrenne et al. 2003). It covers the energy range 20–8000 keV (with an energy resolution varying between 2 and 6 keV) and has an angular resolution of ~3° and a total field of view of ~25° FWHM. One of its primary objectives is the detailed study and mapping of diffuse gamma-ray line emission. The *INTEGRAL* observing program has two main parts: the Core Program, which is essentially guaranteed time for the teams of scientists who built and operate *INTEGRAL*, and the Open Program, which comprises competitively selected observations of guest investigators. The Core Program includes a deep exposure of the central radian of our Galaxy, repeated scans of the Galactic plane, and selected point-source observations. A large fraction of the Open Program observations were in or near (within ±20°) the Galactic plane. The coauthors of this paper include most of the guest investigators selected for observations within ±20° of the Galactic plane during the first year of *INTEGRAL* observations. We restrict ourselves in this paper to the Galactic plane outside of the central region ($|l| > 40°$). Results from the central region have been presented in other papers (Jean et al. 2003a, 2004; Knödlseder et al. 2003; Lonjou et al. 2004; Weidenspointner et al. 2004; J. Knödlseder et al. 2005, in preparation). Figure 1 is an exposure map of *INTEGRAL* observations during the period 2003 December to 2004 October. The combined data set, including Core Program, Open Program, and calibration observations, amounts to 8.9 Ms of exposure of the Galactic plane, of which 2.1 Ms is in the region $|l| > 40°$. Solar and trapped particles can cause rapidly changing instrument background levels that can be misinterpreted as source flux. The data were carefully screened to eliminate such periods using a combination of onboard rates and data from the *GOES* satellites. Isolated points with large deviations that could be a result of either transmission or processing errors were also removed.

[17] π^+ decays into μ^+, which decays into positron.

3. DATA ANALYSIS

In this paper we use the so-called light-bucket method of analysis, since we are interested mainly in broad-scale diffuse Galactic plane emission. In this method all detectors are summed for each pointing, which suppresses the imaging information on the 3° scale of the mask. SPI is then a light bucket collecting all photons in its ~25° FWHM field of view. This mode is useful for studying diffuse emission on spatial scales ≳20° and is likely to be less sensitive to systematic effects than the full imaging mode, which requires an exact knowledge of the detailed properties of the coded-aperture mask and the individual detectors. We use the same Monte Carlo–generated (GEANT) response function as is used in the imaging mode (Sturner et al. 2003), except that we sum the response over all 19 detectors. This work complements that of J. Knödlseder et al. (2005, in preparation), which concentrates on the imaging aspects of the instrument, and it provides an independent verification of some of the conclusions reached there.

SPI has a high 511 keV background level due mainly to cosmic-ray interactions in the instrument and surrounding spacecraft (Jean et al. 2003b; Weidenspointner et al. 2003; Teegarden et al. 2004). Some of these interactions make excited nuclei that undergo β^+ decay, which produces a strong 511 keV background line. The 511 keV signal-to-background ratio for observations in the central region of the Galaxy is typically only a few percent. The *INTEGRAL* spacecraft is in a highly eccentric orbit

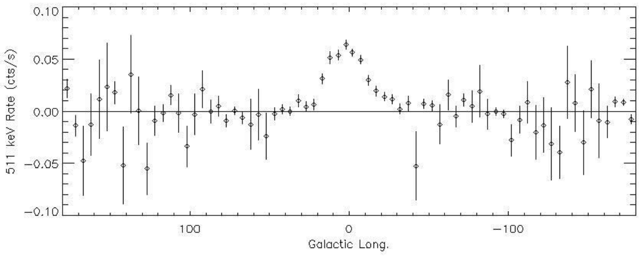

FIG. 2.—*INTEGRAL* SPI background-subtracted 511 keV count rate as a function of Galactic longitude for the region $-10° < b < 10°$. The significant excess centered at $l = 0°$ is mainly due to the 511 keV bulge component. No significant flux is seen in the region $|l| > 40°$. The large differences in error bars are due to widely varying exposures in different parts of the Galactic plane.

with an initial apogee of 155,000 km and perigee of 9000 km. *INTEGRAL* therefore spends most of its time outside of the magnetosphere, which means that the background is relatively stable in comparison with that for a low Earth orbiting instrument (e.g., OSSE, *HEAO* C-1). The cosmic-ray flux typically varies by 5%–10% over time periods of the order of 1 yr resulting in an instrumental background at 511 keV whose variation is of the same order or larger than the measured 511 keV flux. A precise determination of this background is therefore critical to extracting the optimum performance from SPI. In this analysis we have modeled the 511 keV background using various onboard tracers of the primary cosmic-ray intensity (Jean et al. 2003b; Lonjou et al. 2004; Teegarden et al. 2004). Two of these, the rate of saturated events in the germanium detectors (GEDSAT) and the plastic-anticoincidence rate (PSAC), have been found to be the most useful. The former samples cosmic rays $\gtrsim$200 MeV and the latter $\gtrsim$10 MeV. We assume that far from the Galactic plane ($|b| > 20°$) there is no significant 511 keV emission and use these data (3.1 Ms live time) from the first year of operation to determine the best-fit background model. If there were quasi-isotropic 511 keV emission, it would be suppressed in our analysis. We calculated the total 511 keV line count rate by integrating over a 10 keV interval centered at 511.0 keV and subtracted a continuum determined by a simple interpolation between two 10 keV windows on either side of the line. We fitted these data and found that a linear combination of the GEDSAT and PSAC rates is a good background predictor, but that there is a significant long-term monotonically increasing residual in the fit.

A detailed Monte Carlo model for SPI has been implemented under the GEANT software package. An enhanced version of this package, MGGPOD (Weidenspointner et al. 2005), which treats gamma-ray background production in a much more extensive and complete manner, was used. The Monte Carlo background simulations are not accurate enough to make absolute predictions of the background levels. However, they are useful in identifying the dominant isotopes for background production and their half-lives. Long half-life decays can account for the sort of residual described in the preceding paragraph. The Monte Carlo analysis identified ^{65}Zn, a spallation product of germanium with a half-life of 244 days, as a possibly significant contributor to the 511 keV background. We included a term in the model for this decay channel and found that it significantly improved the fit, although the actual value of the half-life was not well-constrained by the available data. ^{22}Na, with a 2.6 yr half-life, is another possible contributor to the long-term 511 keV buildup; however, its intensity in the simulation is low. The accuracy of the model 511 keV background prediction is estimated to be 0.3%.

4. RESULTS

Figure 2 is a plot of the background-subtracted SPI 511 keV count rate in the $-10° < b < 10°$ band as a function of Galactic longitude. A clear peak centered at $l = 0°$ is visible. The first papers of SPI results (Jean et al. 2003a; Knödlseder et al. 2003) reported that this enhanced flux region was well represented by a circularly symmetric Gaussian with a width of 7°–10°. More recent work (J. Knödlseder et al. 2005, in preparation) has found evidence of an asymmetry in the bulge with a latitude width of $13° \pm 5°$ and longitude width of $25° \pm 4°$. This spatial

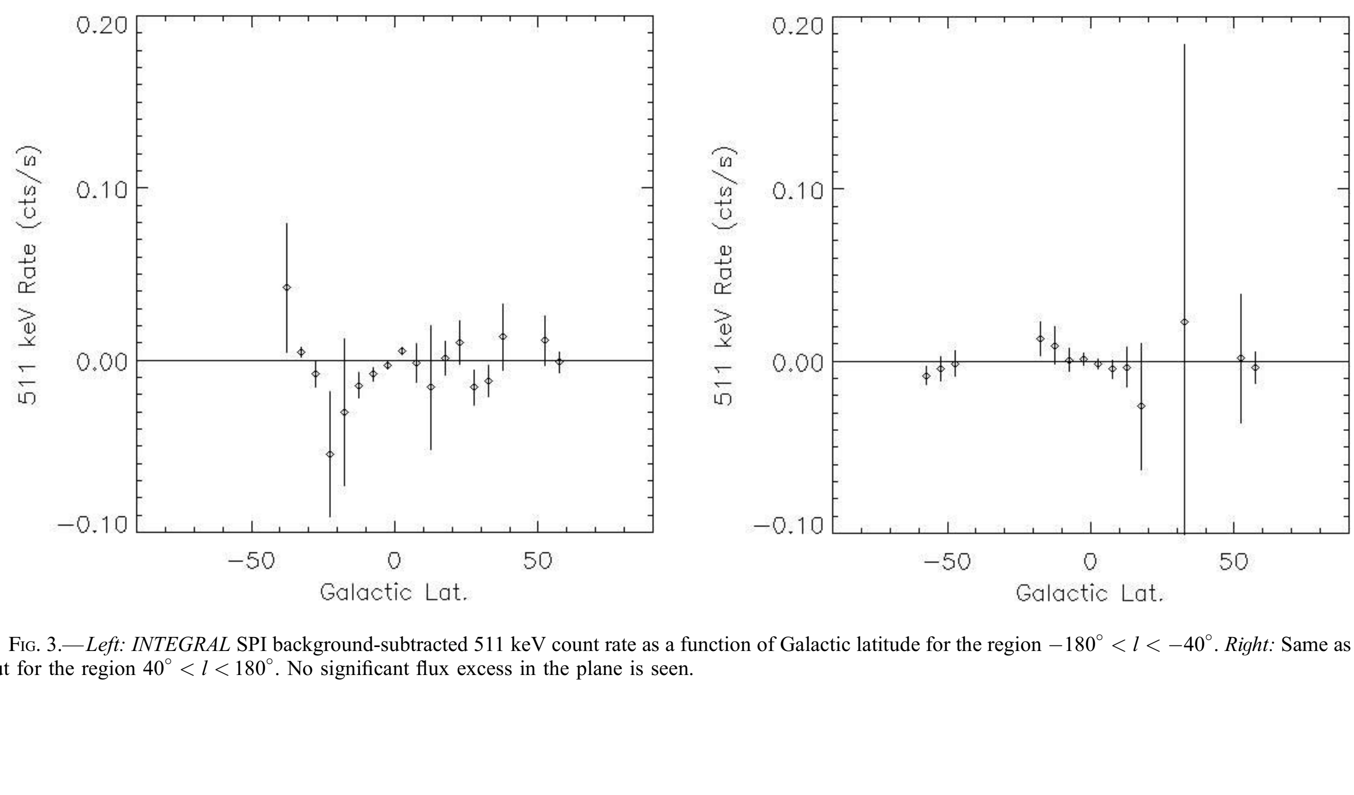

FIG. 3.—*Left: INTEGRAL* SPI background-subtracted 511 keV count rate as a function of Galactic latitude for the region $-180° < l < -40°$. *Right:* Same as left but for the region $40° < l < 180°$. No significant flux excess in the plane is seen.

TABLE 1
Galactic Plane 511 keV Flux Limits

l/b	−175	−165	−155	−145	−135	−125	−115	−105	−95	−85	−75	−65	−55	−45
−15	1.31	1.51	2.89	8.05	8.55	9.49	4.45	2.38	1.82	1.81	2.07	2.12	2.21	2.58
−5	1.17	1.36	2.53	3.42	3.71	3.42	2.35	1.41	1.12	1.29	1.98	2.51	2.14	1.91
5	1.62	2.10	4.03	3.54	3.46	3.17	2.66	1.32	1.13	1.24	2.53	2.79	2.12	2.00
15	5.11	5.79	11.63	9.02	7.23	6.73	6.30	3.47	1.82	3.75	8.17	5.37	2.74	2.17

l/b	45	55	65	75	85	95	105	115	125	135	145	155	165	175
−15	1.97	5.13	5.98	4.68	4.45	4.64	5.39	4.33	5.51	6.46	4.64	4.11	2.86	1.48
−5	1.20	1.52	1.44	1.26	1.75	2.02	2.32	1.89	1.89	3.00	4.32	3.46	2.07	1.33
5	1.18	1.37	1.21	1.14	1.39	2.07	2.37	2.05	1.94	3.54	5.31	4.44	3.28	1.92
15	2.34	3.22	1.64	1.38	1.95	4.31	5.43	4.74	4.68	10.44	18.55	11.35	6.20	6.59

Note.—Upper limits are 90% confidence values in $10^\circ \times 10^\circ$ tiles centered on the given l/b values. Flux units are $\mathrm{cm^{-2}\ s^{-1}} \times 10^{-4}$.

distribution appears to be qualitatively similar to the two-component bulge plus disk description of the OSSE results (Kinzer et al. 2001). Our light-bucket analysis is not very sensitive to these differences in morphology. As a check on our method we have fitted the data with a circularly symmetric Gaussian centered at $l = 0^\circ$, $b = 0^\circ$ and a fixed width of 10°. We derive a total flux of $\sim 1 \times 10^{-3}\ \mathrm{cm^{-2}\ s^{-1}}$, which is consistent with early SPI results (Jean et al. 2003a, 2004). Other authors (Share et al. 1988; Kinzer et al. 2001) have reported higher fluxes from the central region. A possible explanation for these differences is the existence of an extended emission halo to which *INTEGRAL* might not be sensitive. Resolution of this question must await the accumulation of more data and better coverage of regions of the sky away from the Galactic center.

Outside of the $|l| < 40^\circ$ central region there is no evidence of any significant 511 keV emission. The error bars vary widely due to the nonuniform coverage of the Galactic plane. They are smallest in regions where the exposure is deepest, near the Crab ($l = 185^\circ$), Cygnus ($l = 71^\circ$), Vela ($l = -94^\circ$), and Cas A ($l = 116^\circ$). In Figure 3 the 511 keV count rate is plotted as a function of Galactic latitude for two longitude regions, $-180^\circ < l < -40^\circ$ and $40^\circ < l < 180^\circ$. Again, there is no evidence of any significant flux. Even if there were errors in our background model, we would not expect them to be correlated with the SPI pointing direction. The absence of any *relative* enhancement in the latitude distributions in Figure 3 is strong evidence of the absence of detectable 511 keV emission from the Galactic plane.

Upper limits (90% confidence) for the 511 keV flux in the Galactic plane are given in Table 1. The plane outside of the central region has been divided into $10^\circ \times 10^\circ$ tiles. Within each tile the SPI response to a point source anywhere in the tile has been calculated. The average value for this response was used to determine the upper-limit values of Table 1. We estimate a systematic uncertainty in the flux of $\sim 7 \times 10^{-5}\ \mathrm{cm^{-2}\ s^{-1}}$ (because of the uncertainty of the background model), which is added in quadrature to the statistical error in calculating the upper limits. There is significant variation in the values because of the varying exposure. The lowest values ($\sim 1 \times 10^{-4}\ \mathrm{cm^{-2}\ s^{-1}}$) are of the order of 10% of the total flux in the central bulge component. The lowest upper limits are at locations of high exposure, where well-known sources in the Galactic plane were observed for calibration and/or scientific study.

We have used a second method to search for large-scale 511 keV emission from the Galactic plane. We have performed global fits to the entire ($|l| > 40^\circ$) data set using several source distributions. The following emissivity distributions were used:

Old Disk:

$$\rho(R,\ z) = \rho_0 \left(e^{-(a/R_0)^2} - e^{-(a/R_i)^2} \right) \quad (1)$$

(Robin et al. 2003), where $a = R^2 + z^2/\epsilon^2$, $\epsilon = 0.14$, $R_0 =$ 5 kpc (disk scale radius), and $R_i = 3$ kpc (inner disk truncation radius).

Young Disk:

$$\rho(R,\ z) = \rho_0 \left(e^{-\left[0.25+(a/R_0)^2\right]^{1/2}} - e^{-\left[0.25+(a/R_i)^2\right]^{1/2}} \right) \quad (2)$$

(Robin et al. 2003), where $\epsilon = 0.0791$, $R_0 = 2.53$ kpc, and $R_i = 1.32$ kpc.

These emissivities were integrated along the line of sight to produce spatial flux distributions. For the sake of completeness we also included a flat distribution (in Galactic longitude with a Gaussian latitude profile of FWHM 5°). The fits to these distributions all produced results that are consistent with zero 511 keV flux from the Galactic plane (outside of the central region). The 90% confidence upper limits are: old disk, $4.4 \times 10^{-4}\ \mathrm{cm^{-2}\ s^{-1}}$; young disk, $3.9 \times 10^{-4}\ \mathrm{cm^{-2}\ s^{-1}}$; and flat disk, $5.0 \times 10^{-4}\ \mathrm{cm^{-2}\ s^{-1}}$.

5. CONCLUSIONS

We have analyzed data from the first 10 months of the *INTEGRAL* mission using the so-called light-bucket method, which in principle is relatively less sensitive to systematic effects than the more standard imaging techniques. We have found no significant 511 keV flux from the Galactic plane ($-20^\circ < b < 20^\circ$) outside of the central region ($-40^\circ < l < 40^\circ$). Our method of analysis is sensitive to both point and diffuse sources. The values of the limits in 10° tiles vary between 1.2×10^{-4} and $1.9 \times 10^{-3}\ \mathrm{cm^{-2}\ s^{-1}}$ because of large variations in the exposure in different regions of the Galactic plane. We have also performed global fits of the entire data set that set limits on the total 511 keV flux in the Galactic plane. These values limit the broad-scale 511 keV emission in the outer region of the plane to less than 40%–50% of that from the central region ($|l| < 40^\circ$). Over the course of the mission (expected to last >5 yr) the exposure will deepen and likely become more uniform, which will lead to better and more uniform limits and, perhaps, to detections.

INTEGRAL is a project of the European Space Agency in which NASA is a contributing partner.

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