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Early SPI/INTEGRAL measurements of 511 keV line emission from the 4th quadrant of the Galaxy*

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Abstract. We report the first measurements of the 511 keV line emission from the Galactic Centre (GC) region performed with the spectrometer SPI on the space observatory INTEGRAL (International Gamma-Ray Astrophysics Laboratory). Taking into account the range of spatial distribution models which are consistent with the data, we derive a flux of $9.9^{+4.7}_{-2.1} \times 10^{-4}$ ph cm^{-2} s^{-1} and an intrinsic line width of $2.95^{+0.45}_{-0.51}$ keV (*FWHM*). The results are consistent with other high-spectroscopy measurements, though the width is found to be at the upper bound of previously reported values.

Key words. gamma rays: observations – line: profiles – Galaxy: center

1. Introduction

Line emission at 511 keV from the GC region has been observed since the early seventies in balloon and satellite experiments. The line was discovered at an energy of 476 ± 26 keV (Johnson et al. 1972), so the physical process behind the emission was initially ambiguous and firm identification had to await the advent of high resolution spectrometers. In 1977, germanium (Ge) detectors, flown for the first time on balloons, allowed the identification of the narrow annihilation line at 511 keV. Its width turned out to be only a few keV (Albernhe et al. 1981; Leventhal et al. 1978). The eighties were marked by ups and downs in the measured 511 keV flux through a series of observations performed by the balloon-borne Ge detectors (principally the telescopes of Bell-Sandia and GSFC). The fluctuating results were interpreted as the signature of a compact source of annihilation radiation at the GC (see e.g. Leventhal 1991). Additional evidence for this scenario came initially from HEAO-3 (Riegler et al. 1981) reporting variability in the period between fall 1979 and spring 1980. Yet, during the early nineties, this interpretation was more and more questioned, since neither eight years of SMM data (Share et al. 1990) nor the revisited data of the HEAO-3 Ge detectors (Mahoney et al. 1993) showed evidence for variability in the 511 keV flux. Throughout the nineties, CGRO's Oriented Scintillation Spectrometer Experiment (OSSE) measured steady fluxes from the galactic bulge and disk component and some spatial information about annihilation emission was extracted from the OSSE, SMM and TGRS experiments (Purcell et al. 1997; Milne et al. 2001). A possible additional component at positive galactic latitude was attributed to an annihilation fountain in the GC (Dermer & Skibo 1997). A summary of the key parameters measured by high resolution spectrometers is given in Table 1.

We report the first measurements of galactic 511 keV gamma-ray line emission performed by the spectrometer SPI on INTEGRAL. SPI is a coded-mask telescope with a fully-coded field of view of 16° that uses a 19 pixel high-resolution Ge detector array resulting in an effective area of about 75 cm^2 at 511 keV (Vedrenne et al. 1998).

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2. Data analysis

The data analysed in this work were accumulated during the first year's GC Deep Exposure (GCDE) and Galactic Plane

Table 1. The GC 511 keV line measured by more recent high resolution spectrometers. The uncertainties quoted for the SPI results include the effects of the range of models discussed in the text (Sect. 3).

Instrument	Year	Flux [10^{-3} ph cm^{-2} s^{-1}]	Centroid [keV]	Width ($FWHM$) [keV]	References
HEAO-3[a]	1979–1980	1.13 ± 0.13	510.92 ± 0.23	$1.6^{+0.9}_{-1.6}$	Mahoney et al. (1994)
GRIS[b]	1988 *and* 1992	0.88 ± 0.07		2.5 ± 0.4	Leventhal et al. (1993)
HEXAGONE[b]	1989	1.00 ± 0.24	511.33 ± 0.41	$2.90^{+1.10}_{-1.01}$	Smith et al. (1993)
TGRS[c]	1995–1997	1.07 ± 0.05	510.98 ± 0.10	1.81 ± 0.54	Harris et al. (2000)
SPI	2003	$0.99^{+0.47}_{-0.21}$	$511.06^{+0.17}_{-0.19}$	$2.95^{+0.45}_{-0.51}$	this work

[a] Assuming a point source.
[b] Flux in the field of view (17° and 18° for GRIS and HEXAGONE respectively).
[c] Gaussian-shape source ($FWHM$ 30°).

Scan (GPS), executed as part of INTEGRAL's guaranteed time observations (see Winkler 2001). We used data from 19 orbits from March 3rd to April 30th, 2003, amounting to a total effective exposure time of 1667 ks. The GCDE consists of rectangular pointing grids covering galactic longitudes $l = \pm 30°$ and latitudes $b = \pm 10°$, with reduced exposure up to $b = \pm 20°$. The GPS consists of pointings within the band $b = \pm 6.4°$ along the galactic plane. For details see Winkler (2001). The present data are from 1199 pointings with an average exposure of 1400 s per pointing.

As a result of data sharing agreements, the results presented here are limited to the galactic quadrant $l = 270°$–$360°$ but, in accordance with those agreements, data from pointings in the entire GCDE region $l = \pm 30°$ have been taken into account in the analysis.

For each pointing and each of the 19 Ge detectors, the SPI event data were gain corrected and binned into 0.25 keV wide bins. The gain correction was performed for each orbit to account for long-term gain drifts that arise from temperature variations of the detectors. The instrumental background lines employed for the calibration were those at 438.64 keV (^{69}Zn), 1107.01 keV (^{69}Ge), and 1778.97 keV (^{28}Al). Within this range a linear relationship between raw channel and calibrated energy has been found sufficient and leads to an absolute energy calibration of better than 0.05 keV at 511 keV. Note that the data were taken in a period immediately following the first SPI detector annealing procedure, when the energy resolution was optimal. On average, we obtained an instrumental energy resolution of 2.16 ± 0.03 keV full width at half maximum ($FWHM$) at 511 keV.

The instrumental background at the energy of interest is comprised of a strong instrumental 511 keV line superimposed on a continuum spectrum. Typically, the expected signal-to-background ratio for the observation of the GC is 2.5% for the line only, and of the order of 1.25% when also taking into account the underlying continuum.

The instrumental background in the 511 keV line region has been modelled by two components. The first model component describes the continuum below the instrumental 511 keV line and is based on the background level in energy bands adjacent to the line. The second model component describes the instrumental 511 keV line in intensity and shape and is based on observations of an empty field that is assumed to be free of celestial 511 keV line emission. The time variation of both components has been modelled using the rate of saturating events in the Ge detectors. Detailed studies of the time variability of the instrumental SPI background have shown that over wide energy bands, and in particular for the instrumental 511 keV line, the background variations follow the variations of the saturating event rate. This correlation can be understood as follows. Impinging cosmic-ray protons produce high energy secondary particles (p, n, π^+, γ...) in inelastic interactions with instrument nuclei. When the primary or secondary particles release more than ~8 MeV in a Ge detector they trigger a saturating event. The positrons responsible for the 511 keV background line are related to this secondary flux since they are produced (1) by the decay of β^+ isotopes induced by nuclear reactions of secondary n and p with instrument material, (2) by pair creation from secondary γ's and (3) by the decay of π^+. Similarly, the continuum background rate underneath the line varies with the saturating event rate since it is mainly due to the decay of radioactive isotopes produced in Ge detectors. The yield of these isotopes is mostly proportional to the secondary neutron flux impinging on Ge detectors (see Naya et al. 1996).

The continuum component was taken to be independent of energy but to follow the number, $S_{p,d}$, of saturating events in the detector. Thus the predicted number of continuum background counts, $B^{\rm cont}_{p,d,e}$, in detector d and energy bin e during pointing p is given by

$$B^{\rm cont}_{p,d,e} = F \Delta_e \frac{S_{p,d}}{\sum_{p'} S_{p',d}} \sum_{p'} \frac{\sum_{e'} N_{p',d,e'}}{\sum_{e'} \Delta_{e'}}. \quad (1)$$

Here Δ_e is the width of the spectral bin (in keV), and $N_{p,d,e}$ is the number of observed counts. The sum over e' is taken over the adjacent energy intervals 485–500 keV and 520–550 keV and that over p' over all GC region pointings. The normalising factors in the denominators have been defined such that the factor F is nominally unity.

The level and spectral shape of the instrumental 511 keV line component was determined from observations of empty fields, labelled "off", and is given by

$$B^{\rm line}_{p,d,e} = G \Delta_e \frac{S_{p,d}}{\sum_{p'} S^{\rm off}_{p',d}} \sum_{p'} \left(\frac{N^{\rm off}_{p',d,e}}{\Delta_e} - \frac{\sum_{e'} N^{\rm off}_{p',d,e'}}{\sum_{e'} \Delta_{e'}} \right) \quad (2)$$

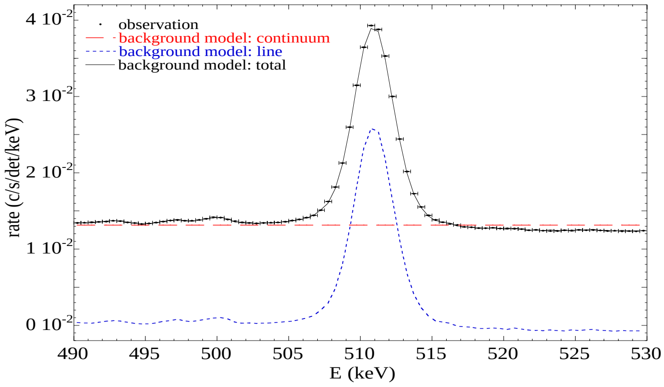

Fig. 1. Raw spectrum and background model components.

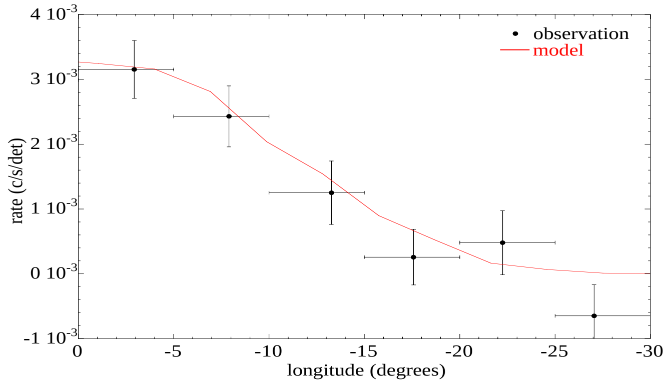

Fig. 2. Rate induced by galactic 511 keV photons as a function of longitude. The response to a Gaussian source ($FWHM$ = 10°) is also shown for comparison.

where $S^{\rm off}_{p,d}$ and $N^{\rm off}_{p,d,e}$ are the number of saturating events, and the number of observed counts for the empty field observation. The sum over e' is taken over the same adjacent energy intervals that were used for the continuum component while p' now runs over all "off" pointings. The factor G is analogous to the F in Eq. (1).

Figure 1 shows the raw spectrum (summed over all pointings and detectors) together with the two background model components.

To assess the systematic uncertainties of our approach, we used 3 different empty field observations for background modelling: (a) a 820 ks observation of the Cygnus region performed during the performance and verification phase, (b) a 718 ks observation of the LMC region, and (c) a 450 ks observation of the Crab nebula performed after the first annealing.

The use of the rate of saturated event rates was found to predict short term variations very well, but if the factors F and G are held at unity, systematic residuals with an amplitude of up to 2% are found over times greater than a few days. This leads to relatively large uncertainties in the measurement of the flux of the cosmic 511 keV line and, since the main morphological information is contained in the temporal modulation, it could introduce a systematic error in the determination of its spatial distribution.

The systematic uncertainties are considerably reduced by introducing a moderate number of free parameters in the analysis. It turned out that the morphology study is best performed allowing a different value of G for each of the 19 orbits. In this way, only the short-term time variability (<3 days) is predicted by the background model while the long-term variability is regarded as an unknown. For line profile studies, it is the energy dependence which is more important and the factors F and G were both fitted on a "per energy bin" basis. With this background modelling, the spatial distribution models discussed below all have acceptable χ^2 values (probability $\gtrsim$0.5).

3. Results

A first indication of the distribution of the emission can be obtained by plotting the mean background subtracted counting rate in the line, averaged over all detectors, as a function of galactic longitude. This is shown in Fig. 2. The profile expected given the 16° $FWHM$ field of view, for Gaussian shaped source of 10° $FWHM$ is also shown[1].

A more quantitative approach is possible by taking into account the spatial and temporal coding by the instrument and fitting to the data a model of the spatial distribution that has one or more components. The components can be point sources, Gaussian or other geometric forms, or arbitrary maps corresponding to known distributions. The intensities of the components are adjusted to maximize the likelihood that the model gives rise to the observed distribution of counts in the line (a band 508–514 keV was used), binned by detector and by pointing. A background, computed as described in Sect. 2, is included in the modelling.

Models based on Gaussian functions centred on the GC require a $FWHM$ between 6° and 18° (2σ limits), with a best fit $FWHM$ of 10° (the quoted range includes systematic uncertainties introduced by the background modelling). Models based on uniform emission within a given radius, centred again on the GC, require a diameter between 10° and 26° (2σ limits), with an optimum diameter of 14°.

Analyses with models consisting only of point sources, at positions found in successive iterations by the SPIROS software (Skinner & Connell 2003), show that a single point source is inconsistent with the data. Formally, we cannot exclude the possibility that the emission originates in at least 2 point sources.

To study the 511 keV line profile the data in 1 keV wide energy bins were independently fitted using models of celestial 511 keV gamma-ray line emission distributions on top of the background model. As an example, the resulting photon spectrum obtained using a 10° $FWHM$ Gaussian for the spatial distribution (our best fitting model distribution) is shown in Fig. 3. Line profile parameters have been extracted from these spectra by fitting to the flux values a Gaussian function on top of a constant. Addition of a positronium step does not significantly change the result.

Using Gaussian models with $FWHM$ that vary between our 2σ limits of 6°–18°, we obtain a 511 keV line flux of

[1] In accordance with the above-mentioned data-sharing agreement, only negative longitudes are shown.

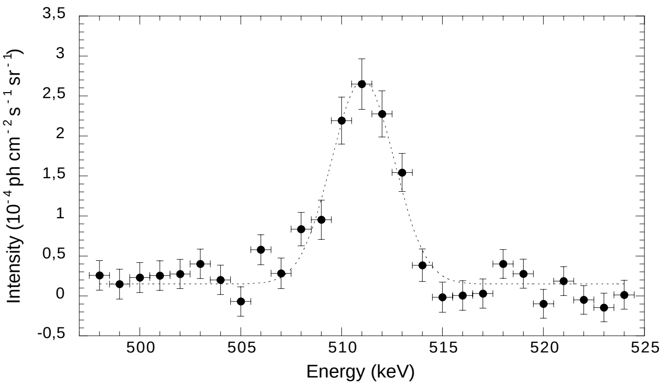

Fig. 3. 511 keV flux spectrum obtained using a Gaussian centred on the GC with a *FWHM* of 10°.

$9.9^{+4.7}_{-2.1} \times 10^{-4}$ ph cm^{-2} s^{-1}, a line centroid of $511.06^{+0.17}_{-0.19}$ keV and an observed line width of $3.66^{+0.36}_{-0.41}$ keV (*FWHM*). We note that, in particular for the flux estimates, the uncertainties quoted are dominated by the range of models considered. For a specific model they are very much smaller (see below). Subtracting quadratically the instrumental line width of 2.16 ± 0.03 keV at 511 keV results in an intrinsic width of $2.95^{+0.45}_{-0.51}$ keV (*FWHM*) for the astrophysical line. Using different methods of treating the instrumental background (different "off" observations and different adjacent energy bands) provides us with an estimate for the systematic uncertainties in these measures. They amount to $\sim 10^{-5}$ ph cm^{-2} s^{-1} for the line flux, 0.03 keV for the line centroid, and 0.1 keV for the line width.

Trying alternative celestial intensity distribution models mainly affects the 511 keV line flux, while the line position and line width always stay within the quoted uncertainties. For example, if one fits a point source at the GC – despite the fact that such a model is excluded by the data – this results in a flux of $(5.4 \pm 0.5) \times 10^{-4}$ ph cm^{-2} s^{-1}. Fitting a uniform emission with a diameter of 14° around the GC – a model that fits the data almost as well as the 10° Gaussian – results in a flux of $(9.4 \pm 0.8) \times 10^{-4}$ ph cm^{-2} s^{-1}.

4. Conclusions

Preliminary results from the early mission phase show that SPI on INTEGRAL allows a study of the GC 511 keV emission with an unprecedented combination of spectral and angular resolution and of sensitivity. In general the results are consistent with earlier measurements (see Table 1). We can exclude with high significance models in which the source is relatively compact; for a Gaussian source centred at $l = 0°$, $b = 0°$ the 2σ lower limit on the *FWHM* is 6°. This is in the high side of the 3.9°–5.7° *FWHM* range derived from OSSE, SMM and TGRS data (Milne et al. 2000). In the spectral domain, our measurements show that the line width ($2.95\,^{+0.45}_{-0.51}$ keV) is at the upper bound of the range of values previously reported.

In this short communication we have confined ourselves to simple spatial and spectral descriptions of the data. Constraints on distributions suggested by earlier measurements with poorer spatial and/or spectral sensitivity and studies of the positronium emission (evidence for which can perhaps be seen in Fig. 3) will be discussed elsewhere.

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