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Diffuse continuum emission from the inner Galaxy: First results from INTEGRAL/SPI

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Abstract. We present a preliminary analysis of the diffuse hard X- and soft γ-ray continuum emission from the inner Galactic ridge using INTEGRAL/SPI data from the first Galactic Plane Deep Exposure and Galactic Plane Scans. The spectrum is consistent with results from previous experiments. These early results demonstrate the potential of the INTEGRAL mission for improving our understanding of this emission.

Key words. X-rays – gamma rays – galactic structure – interstellar medium – cosmic rays

1. Introduction

The inner Galactic ridge is known to be an intense source of diffuse continuum hard X- and soft γ-ray emission. The hard X-ray emission was discovered in 1972 (Bleach et al. 1972) and has subsequently been observed from keV to MeV energies by ASCA, Ginga, RXTE, OSSE, COMPTEL and most recently by Chandra. While the physical process (e^+e^- annihilation) producing the positron line and positronium continuum is clear, the source of the remaining continuum is not, although nonthermal bremsstrahlung is most likely (Dogiel et al. 2002a). The implied photon luminosity of a few 10^{38} erg s^{-1} is remarkable (Dogiel et al. 2002a). An origin in a point-source population seems unlikely (Tanaka et al. 1999) since there are no known candidate objects, and high-resolution imaging with Chandra shows a truly diffuse component (Ebisawa et al. 2001). Emission by non-thermal processes in the interstellar medium implies a very high luminosity in energetic particles (Dogiel et al. 2002a); mechanisms have been discussed by Valinia et al. (2000a,b) and Tanaka (2002) and a solution to the energetics problem has been suggested by Dogiel et al. (2002b) but the field is quite open. At MeV energies the origin of the emission is also uncertain (Strong et al. 2000). The study of this emission is a key goal of the INTEGRAL mission. The high spectral resolution combined with its imaging capabilities lead to high expectations for investigating the nature of this enigmatic emission.

Apart from its intrinsic interest, reliable modelling of the diffuse emission will be essential for the study of point sources in the inner Galaxy, since it contributes a large anisotropic celestial background.

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2. Data

The INTEGRAL Core Program (Winkler et al. 2003) includes the Galactic Centre Deep Exposure (GCDE) which maps the inner Galaxy ($330° < l < 30°, -20° < b < 20°$) with an exposure time of 4 Ms per year. The full region is covered in one GCDE cycle, and there are two cycles per year. Data from the first cycle are now available and are used for the preliminary study reported here. In addition data from the Galactic Plane Scans (GPS) covering this region were used.

We use data from the SPI (INTEGRAL Spectrometer) instrument; descriptions of the instrument and performance are given elsewhere in this volume (Vedrenne et al. 2003; Attié et al. 2003). The energy range covered by SPI is 20 keV−8 MeV, but here we restrict the analysis to energies up to 1 MeV; above these energies the statistics are smaller and the analysis is more difficult, so is reserved for future work. The data were pre-processed at the INTEGRAL Science Data Centre (ISDC) up to the level containing binned events, pointing and livetime information. 18 orbital revolutions taken from 47−66 were used, including both GCDE and GPS pointings. 1326 pointings were used, as shown in Fig. 1; the total exposure time is 1.6×10^6 s. The exposure per pointing is typically 1800 s, but can be as low as 300 s in cases of high telemetry losses in the early part of the GCDE. The energy calibration is performed using instrumental background lines with known energies; while this is a critical operation for line studies (where sub-keV accuracy is required), for continuum studies a standard calibration (∼1 keV accuracy) is quite adequate. The energy binning is logarithmically spaced with $\Delta \log_{10}(E) = 0.0543$. Only single detector events are used here.

The instrumental response is based on extensive Monte Carlo simulations and parameterization (Sturner et al. 2003);

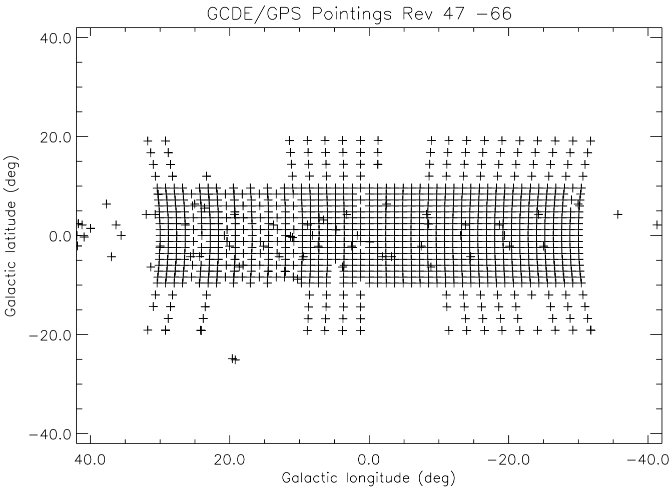

Fig. 1. INTEGRAL pointings used in this work.

this has been tested on the Crab in-flight calibration observations and shown to be reliable to better than 20% in absolute flux at the current state of the analysis.

Since INTEGRAL data are dominated by instrumental background, the analysis needs to have good background treatment methods. In the present work the background ratios between detectors are taken from observations at high latitudes in revolutions 12 and 13 ("OFF" observations)[1]. Although several months elapsed and an annealing operation was performed between the OFF observations and the GCDE, the detector ratios are found to be predictable to better than 1% (standard deviation 0.47%, 0.39%, 0.35% at 60 keV, 300 keV, 900 keV), as estimated by comparing the average ratios for the entire GCDE with the OFF ratios. Hence the error in the adopted ratios is not expected to have large effect on the results reported here[2]. An estimate of the effect of background systematics was performed as described in the next section.

An example of an image of the inner Galaxy using GCDE data is given in the paper on maximum entropy imaging (Strong 2003). Although this image shows indications of diffuse emission, the exposure is not yet sufficient to use imaging as a basis for analysis; in any case spectral extraction is done best by spatial model fitting, as now described.

3. Method

We use the program *spidiffit* which fits the data to a linear combination of input astronomical skymaps (e.g. HI and CO surveys, emission models) and point sources, together with background components. The fit is performed by maximum-likelihood with one parameter per component and energy range. The background is fitted per pointing using a template for the ratios between detectors from the OFF observations. Hence the time-dependence of the background is explicitly determined from the data themselves on the assumption of constant detector ratios. *spidiffit* is available from the INTEGRAL Science Data Centre and a full description is given in the User Manual[3].

As a check on the systematics, an alternative spectrum was generated using a background ratio template obtained by averaging over all the GCDE pointings, so that the celestial signal is suppressed in the background estimate. Although the latter is not the method of choice since the signal cannot be entirely eliminated in the background estimate, the comparison with the spectrum obtained using the OFF background provides a good measure of the systematic errors.

Since the distribution of the emission is unknown but certainly correlated with tracers of large-scale Galactic structure, we include line-of-sight integrated HI and CO surveys (which trace the atomic and molecular gas) as basis models. In addition, since the positronium emission is an important source of continuum below 511 keV and is believed to include in addition a component more concentrated towards the Galactic centre than the gas tracers (Kinzer et al. 2001; Milne et al. 2002; Jean et al. 2003; Knödlseder et al. 2003), and noting that Kinzer et al. (2001) and Milne et al. (2002) found no significant difference between the line and continuum annihiliation angular distributions, we include also a Gaussian with *FWHM* 10° centred on $l = b = 0$. Note that each fitted component has an independent spectrum so that it can be separated in the fitting; the sum of the diffuse components then gives the total diffuse emission spectrum of the inner Galaxy. Additionally we remark that a coded-mask telescope is only sensitive to flux contrasts, so isotropic emission is suppressed.

There are many high-energy point sources in the inner Galaxy; the brightest ones for SPI are visible in the image in Strong (2003). 4U1700-377 and 1E1740-2942 have hard spectra and have high fluxes. In principle all known sources should be included in the analysis; in the present work we restrict ourselves to the four brightest ones: 4U1700-377, 1E1740-2942, H1741-322 and GS1826-238. At low energies our diffuse spectrum is probably contaminated by additional point sources not included in our model. Because of the imaging capability of SPI, the signatures of sources and diffuse emission are very different, so that a large contamination is not expected, although a detailed study of the effect must be made in future. In any case most of the sources have steep spectra so the contribution to the total emission falls rapidly above 50 keV.

4. Results

Figure 2 shows the spectrum of total diffuse continuum emission from the inner Galaxy, $340° < l < 20°, |b| < 5°$. The spectrum using the average over GCDE pointings for the background detector ratio template (described in Sect. 3) is very similar, and allows an estimate of the systematic errors due to this effect of ~50% for each spectral point. The formal statistical errors are mostly much smaller than this due to the large photon counts, so the error bars shown are based on this estimate of the systematic errors. At the top of the energy range

[1] No appropriate OFF data were available from after the GCDE at the time of this analysis.

[2] This test is conservative since the reported deviations can in part be due to the Galactic signal in the "ON" data.

[3] Available from the INTEGRAL Science Data Centre at `http://isdc.unige.ch`

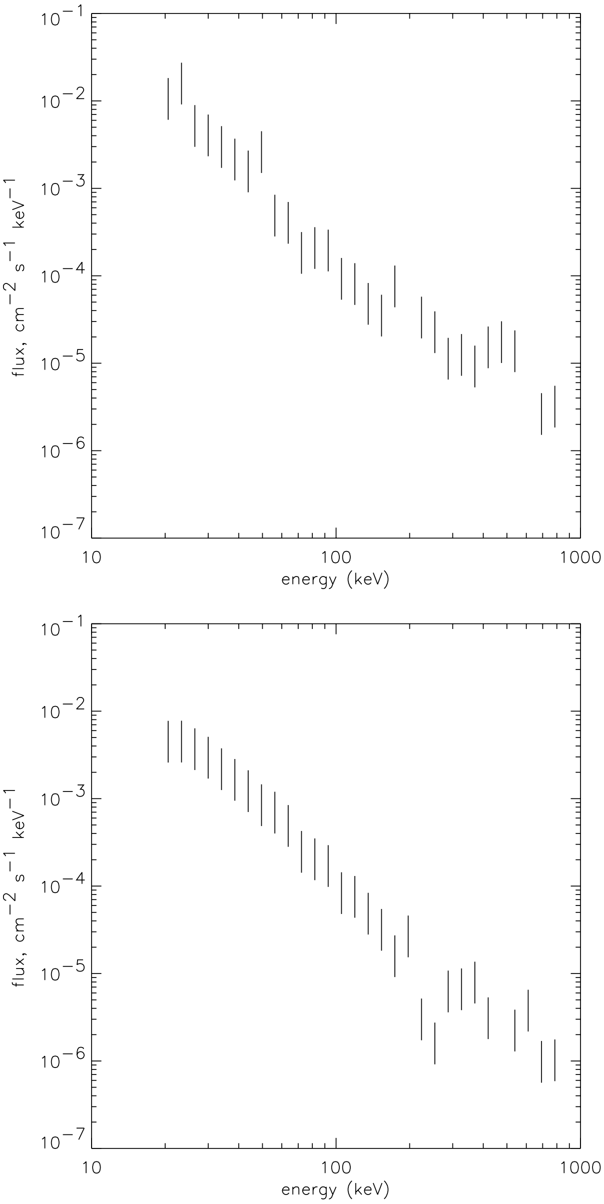

Fig. 2. *Upper*: γ-ray spectrum summed over diffuse components for $340^\circ < l < 20^\circ, |b| < 5^\circ$; *lower*: sum of point sources included in the fit.

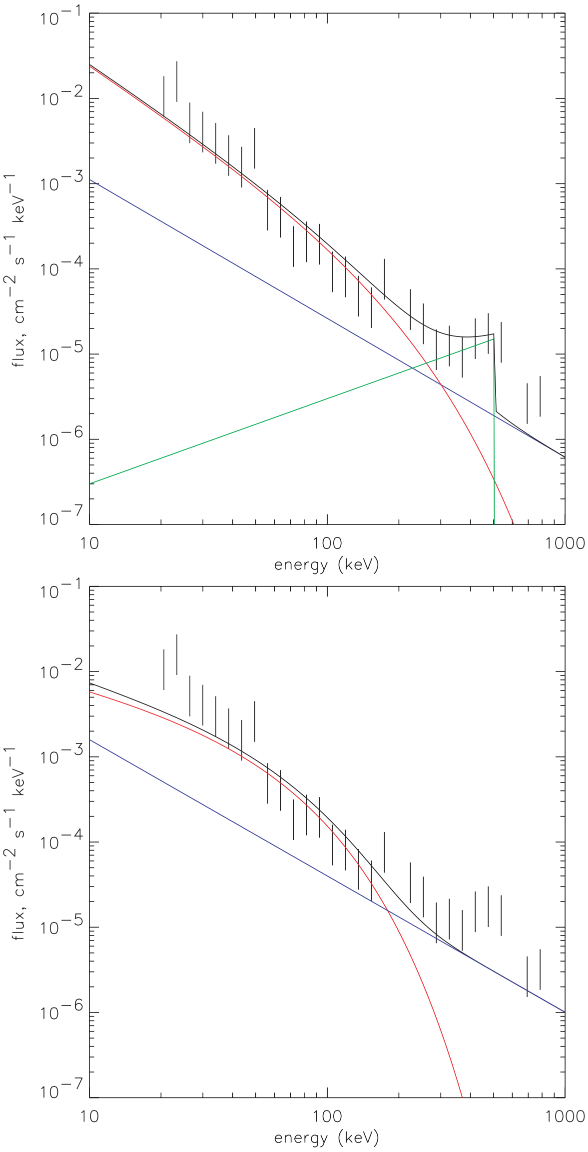

Fig. 3. *Upper*: Comparison of SPI diffuse spectrum (as Fig. 2 upper) with OSSE spectrum around $l = b = 0$ from Kinzer et al. (1999), with components: exponentially cutoff power law (red), high-energy continuum power law (blue), positronium (green) and total (black). Components are scaled as described in the text. *Lower*: Comparison of SPI diffuse spectrum with RXTE/OSSE spectrum at $l = 33^\circ$ from Valinia et al. (2000a) scaled to the solid angle used for SPI. Exponentially cutoff power law (red), high-energy continuum power law (blue) and total (black).

the statistical errors are comparable to the adopted systematic errors. There will also be systematic errors arising from the uncertainty in the response and from the inadequacy of the skymap model; such systematics from the model are difficult to quantify, and would require the evaluation of many models which is beyond the scope of this preliminary analysis.

Figure 3 compares the total diffuse with the total source spectrum; the fluxes are comparable, with the diffuse dominating at all energies, while the sources are dominated by one (4U1700-377). The diffuse emission and the summed sources have quite distinct shapes, the diffuse showing a hardening with increasing energy relative to the sources, as expected.

5. Discussion

As expected the spectrum has approximately a power-law form. There is clear evidence for a positron annihilation component through the positronium edge at 511 keV. Note that the 511 keV line itself is suppressed here due to the broad energy binning. Our spectra can be compared with results from other instruments, but precise comparison is difficult due to the differing regions observed, different instrumental responses, different models assumed, as well as the diverse ways in which results are presented (per radian, per FOV etc.). As an example we compare with the OSSE spectrum for the Galactic centre region given by Kinzer et al. (1999). To do this, we assume their "per radian" spectrum applies to the entire inner radian with suitable scaling of the continuum and positronium components. As shown in Fig. 3, a factor of 0.5 for the continuum and 0.3 for positronium matches our spectrum; this is plausible since their spectrum used data around $l = b = 0$ with the OSSE $3.8° \times 11.4°$ FOV (but assuming a flat distribution in longitude) while ours refers to the region $340° < l < 20°$. Hence the positronium is lower in our spectrum due to its concentration to the region around $l = 0$. Note that the scaling factors used are only intended to be indicative. We also compare with a combined RXTE/OSSE spectrum (Valinia et al. 2000a), for the continuum only, at $l = 33°$; since those results are quoted for the RXTE 1° field-of-view, they are here scaled to the same solid angle as used for SPI, assuming a latitude FWHM of 5°.

Our spectrum is apparently consistent with previous work at least as far as a comparison can be made. A detailed quantitative comparison of absolute fluxes is beyond the scope of this paper, but will be addressed in future.

6. Conclusions

Our first attempt to analyse the SPI data for diffuse continuum emission illustrates the potential of the excellent data provided by SPI. Our spectrum is consistent with previous results. The results should however be treated as preliminary. The advantage of SPI over other missions covering this energy range will clearly be the high energy resolution (not exploited here) and the imaging response which allows the many sources to be explicitly accounted for, including information from the other instruments on INTEGRAL. In addition the large-scale coverage of the sky will be an advantage over previous missions which studied only restricted regions.

The next steps will be to include the full year's GCDE and also the GPS data which extend the coverage to the entire Galactic plane. In addition Open Program data will be included as it becomes public. Both the number of model components and the number of fitted sources will be increased as necessary to give a good representation of the sky at INTEGRAL energies. The full energy resolution of SPI will also be exploited. Detailed model comparisons and evaluation of systematics will then become possible, and which will provide a step towards a better understanding of the diffuse emission.

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