PROCEEDINGS OF SCIENCE

Investigations into the origin of the Galactic 511 keV emission with INTEGRAL/SPI

Gerald Skinner∗,[abc] **Pierre Jean**,[d], **Jürgen Knödlseder**,[d] **Peter von Ballmoos**,[d] **and Georg Weidenspointner**,[e f]

[a]*University of Maryland, College Park, MD 20742, USA*
[b]*CRESST, Greenbelt, MD 20771, USA*
[c]*NASA-GSFC, Code 661, Greenbelt, MD 20771, USA*
[d]*CESR, 7, av. du Colonel Roche, Cedex 4, Toulouse 31028, France*
[e]*MPE, Postfach 1312, 85741 Garching, Germany*
[f]*MPI Halbleiterlabor, Otto-Hahn-Ring 6, 81739 München, Germany*
E-mail: skinner@milkyway.gsfc.nasa.gov, Pierre.Jean@cesr.fr, Jurgen.Knodlseder@cesr.fr, Peter.Von-Ballmoos@cesr.fr, Georg.Weidenspointner@hll.mpg.de

Observations with the SPI spectrometer on INTEGRAL have revealed an unexpected asymmetry in the 511 keV positron annihilation radiation from the galactic disk, leading to a suggestion that the creation of the positrons may be linked to Low Mass X-ray Binaries (Weidenspointner et al., 2008). The lifetime of positrons in the Galaxy and the distance that they travel before annihilation are uncertain, but on some assumptions an origin in LMXBs might lead to detectable structure in the 511 keV emission. More data are now available, allowing the conclusions of Weidenspointner et al. to be tested more deeply. We review the current situation and report on an analysis of the entire SPI dataset now available including searches for evidence of 511 keV emission spatially correlated with LMXBs.

7th INTEGRAL Workshop
September 8-11 2008
Copenhagen, Denmark

∗Speaker.

PoS(Integral08)048

1. Introduction

More than 30 years after the discovery of narrow 511 keV gamma-ray emission from the galaxy[1], the origin of the positron whose annihilation it signals is still uncertain. The problem is not a lack of possible mechanisms for their production – Tables 1 and 2 show some of the many that have been proposed. The difficulty is in distinguishing between them.

511 keV line observations tell us most directly about the final demise of the positrons rather than their origin. The positronium fraction and the shape of the line reflect the circumstances in which the annihilation with an electron took place and the galactic distribution of the emission indicates where it occurred. The positronium fraction has been found to be close to unity (0.94±0.06 [2]; 0.92±0.09 [3]) and the line shape shows evidence of both a narrow component and a wider one. Together these findings indicate that annihilation takes place partly in warm neutral gas regions and partly in warm ionized ones, with at most a small fraction in grains [4].

One constraints on the origin of the positrons comes from consideration of the total flux. Assuming a steady state, any proposed mechanism must be able to account for a production rate that balances the annihilation rate of $\sim 10^{43}$ s^{-1}. Although this may exclude some processes as being the *sole* source of the positrons, for many others the number of positrons that can be generated is in excess of those needed and the question becomes one of what fraction escape the immediate, optically thick, locality of their birth and slow down and annihilate producing a narrow line rather

Origin	Process(es)	References
Galactic Supernovae	a	[13]
Galactic Supernovae + escape from the disk	a	[10, 11]
Novae	a	[14, 15]
Hypernovae/GRB explosions in the galaxy	f	[16 – 18]
LMXBs	f ?	[19]
HMXBs / Micro-Quasars	f	[20]
Wolf-Rayet stars	a	[21]
Red Giants	a	[22]
Pulsars	d	[23]
Millisecond pulsars	d	[24]
Cosmic Ray interactions with matter	b, c	[25]
Dark matter (de-excitation from an excited state)	g	[26]
Light (MeV) dark matter	h	[27]
Sgr A*	b, f	[28 – 30]
Decay of excited primordial WIMPS	i	[31]
Milli-charged fermionic dark matter	h (or i)	[32]
Anti-matter nuggets	j	[33]
Color superconducting dark matter droplets (strangelets)	j	[34]

Table 1: Some of the possible origins that have been suggested for the galactic positrons. The second column indicates the fundamental process that might be involved – see Table 2. References only examples and are not intended to be comprehensive.

PoS(Integral08)048

(a)	β^+ radioactive decay	$N^* \rightarrow N + e^+$
(b)	Pion production and decay	$N + p \rightarrow \pi \rightarrow e^+$
(c)	Decay of nuclei excited by cosmic rays	$N + p \rightarrow N^* \rightarrow N + e^+$
(d)	Creation by photon in magnetic field	$\gamma + \mathscr{B} \rightarrow e^+ + e^-$
(e)	Creation by photon in electric field	$\gamma + \mathscr{E} \rightarrow e^+ + e^-$
(f)	Photon-photon (e.g. in e^+e^- plasma)	$\gamma + \gamma \rightarrow e^+ + e^-$
(g)	Dark matter collisional excitation and decay	$D + D \rightarrow D^* \rightarrow D + e^+ + e^-$
(h)	Dark matter annihilation	$D + \bar{D} \rightarrow e^+ + e^-$
(i)	Dark matter decay of excited state	$D^* \rightarrow D + e^+ + e^-$
(j)	Primordial antimatter	$e^+ \ (+p^-)$

Table 2: Processes leading to the production (or existence) of positrons. N represents a nucleus, D a dark matter particle. Not all the products are shown. (Extended from [15]).

than annihilating in flight or escaping the Galaxy.

In the case of some production mechanisms that have been considered, other constraints are imposed by limits on other signatures that would be expected to accompany the 511 keV gamma-rays. In particular it has been argued that some positron production mechanisms that might otherwise be considered can be excluded from consideration of limits on high energy gamma-ray continuum flux. For example neutralino-neutralino annihilation could produce the positrons from the decay of the pions produced, but high energy gamma-rays would also be produced at levels inconsistent with EGRET limits [6]. Again if the positrons are produced in $p-p$ collisions following accretion events onto a galactic centre black hole, nuclear de-excitation lines would be expected to accompany the 511 keV one [7]. Similarly it has been suggested that any mechanism in which the positrons are born with an energy greater than a few MeV would lead to the associated production of higher energy gamma-rays at levels inconsistent with observations [5]. However, recently it has been pointed out that this constraint may be alleviated if one considers the distribution of the emission [8].

Concerning the distribution of the annihilation radiation, it has long been known that there is both a strong galactic bulge component and emission from the disk. The bulge component is found to be accurately centred on the the centre of the galaxy. In recent measurements it is found not to be well modelled by a single Gaussian function but to be better described by a combination of two such functions with full-width-at-half-maximum $3.4^{+0.6}_{-0.8}$ and $11.6^{+6.0}_{-2.5}$ degrees respectively [9]. The galactic disk emission has proved to be relatively diffuse and difficult to observe. The bulge-to-disk ratio is difficult to measure precisely because of uncertainty about the latitude extent of the emission and more particularly about the influence of a possible very diffuse 'halo' component. It is, however clear that the luminosity bulge-to-disk ratio is $\sim$2–3, much higher than would be expected based on many theories. Recently Weidenspointner *et al.* [9] (here 'W08') reported measurements, discussed below, of the disk emission which showed a surprising asymmetry.

To use the galactic distribution of the positron annihilation radiation as a clue to the origin of the positrons requires some degree of understanding of their propagation through the interstellar medium and in particular how far they travel from the site of their birth to that of their annihilation.

An exception is in the case of the last two postulated origins in Table 1, for which annihilation is assumed to take place *in situ* (with the implication that proponents of these ideas must explain the line width/shape observations mentioned above). Annihilation in flight can occur with a significant probability if the positron energy is high enough, but if a narrow line is to be produced, the positrons must slow down, typically to less than ∼10 eV, before annihilation. Starting with ∼MeV energy and with a typical density warm ISM density of 0.5 cm^{-3}, the slowing-down time is $\sim 10^5$ y [10, 11]. Annihilation then occurs over a comparable timescale. During much of the slowing-down time their speed is a large fraction of *c*, so the path traversed can be up to ∼50 kpc. In the presence of scattering and of a magnetic field, the radial distance that they reach from their origin is of course much less. Estimating this distance is complex, depending in particular on the structure and turbulence of the magnetic fields. Jean *et al.* [4] (see also [12]) have treated the problem as a diffusion one and conclude that it is less than about 50 pc unless the positrons reach regions of hot (ionized) ISM, where the lifetime and radii reached are both very much greater. Prantzos [10] using simple arguments, and Higdon *et al.* [11] based on detailed Monte Carlo simulations, have argued that positrons originating in the galactic plane can escape the disk and travel large distances. Importantly, both argue that they may then be carried by the galactic magnetic field to the bulge and annihilate there, leading to an enhanced bulge-to-disk ratio.

Thus it is not clear to what extent the sky distribution of the 511 keV annihilation radiation carries information about the distribution of the sites of the positron origin, but it is not excluded that the two correspond, perhaps with a blurring on a scale of 0.1–1 kpc, corresponding to ∼1–10° at galactic centre distances. It is at very least one of the few observables that we have, and SPI is allowing our knowledge of the form of the distribution to be refined.

2. 511 keV emission from the galactic disk and a possible link with Low Mass X-ray Binaries (LMXBs)

As was mentioned above, W08 have reported a detection of 511 keV emission from the Galactic disk. The total disk flux that they measured was similar to that reported from OSSE measurements [15] but SPI allows more detailed information about the structure of the emission to be deduced. Unexpectedly, the SPI observations showed a strong asymmetry in the disk emission, with that at negative longitudes 1.8 times stronger than the emission from the positive side. Fig. 1a shows an image reconstructed from the data. In retrospect, the OSSE data [15] had also indicated slightly stronger emission at negative longitudes, but the difference was much smaller and not significant. The interpretation of the OSSE data is however complicated by the fact that the model fitted included a “northern latitude enhancement” component that is now thought to have been spurious.

In W08 an interesting similarity was noted between the modelled asymmetric galactic disk component of the 511 keV emission and the distribution of low mass X-ray binaries (LMXBs) seen in hard X-rays (Fig. 1b). This could be suggestive of an association between the origin of the positrons and the hard LMXBs that we see today. There is no known reason for an asymmetric distribution of LMXBs but if it is a real astrophysical effect then it could be that the positrons are actually linked to an underlying LMXB population that those currently visible represent, or to some underlying cause leading to both distributions to show the same effect. In any case the asymmetry provides a new clue hint in the hunt for origin of the positrons.

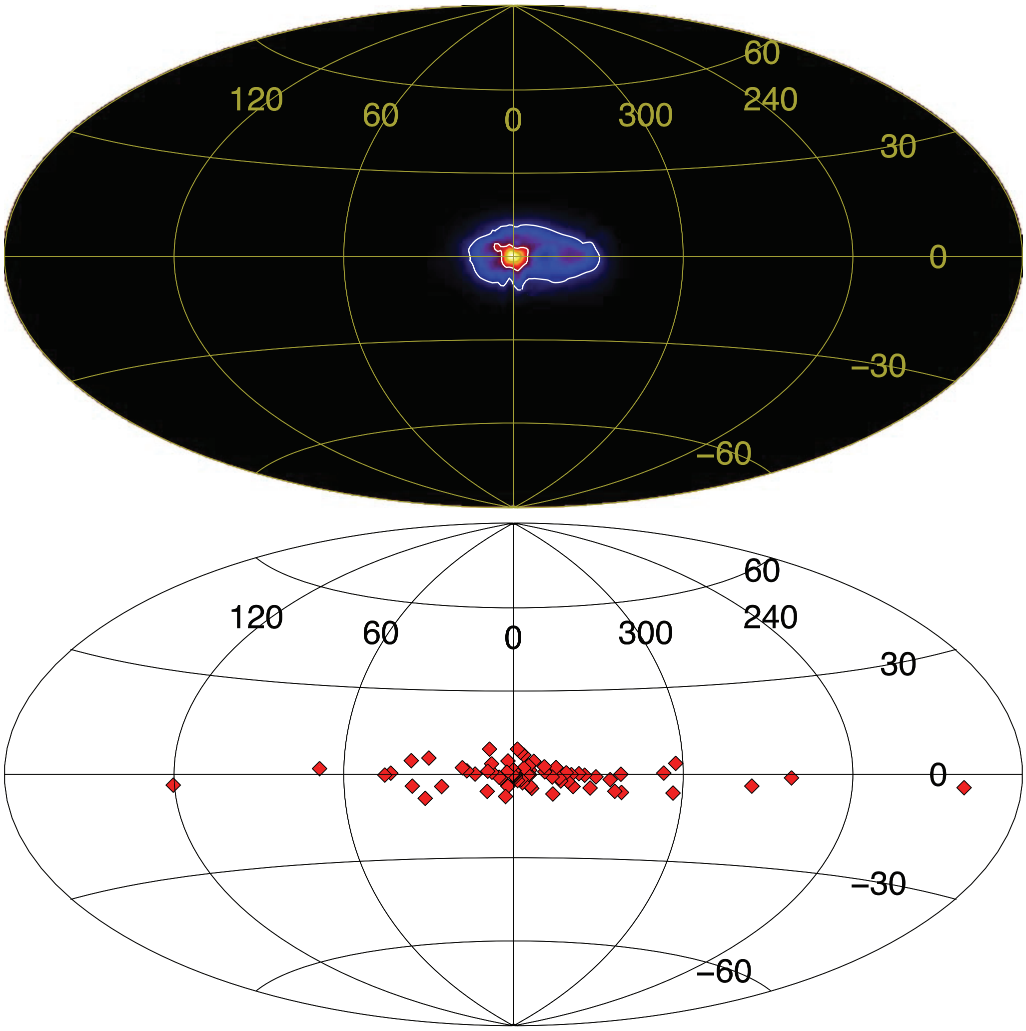

Figure 1: (a) A MREM (multi-resolution expectation maximisation) map of the galactic 511 keV emission in galactic coordinates (W08). (b) The distribution of LMXBs seen in hard X-rays and reported in the third IBIS catalogue [35]

2.1 Updating the results of W08.

We here review the results of the W08 paper in the light of more data and other additional information now available.

Additional recent SPI data add to the 4.5 y of data from 2002 November 23 to 2007 March 13 used in W08. The same model used there has been refitted to all of the data available up to 2008 Aug. As might be expected, the error bars on the amplitudes of the various components are slightly reduced (by about 15%), but the conclusion is unchanged – a provisional updated result is that the disk flux at negative longitudes exceeds that at positive one by a ratio $1.60^{+0.49}_{-0.16}$.

	All	Negative longitude	Positive longitude	Ratio	Probability	Equivalent σ
	LMXBs $\|b\| < 10°$					
3rd IBIS Catalogue [35]	71	45	26	1.73	0.85%	2.39
Swift/BAT 36 month survey [36]	62	35	27	1.30	12.64%	1.14
Liu *et al.* LMXB catalogue (4th ed) [37]	160	94	66	1.42	1.08%	2.30
	511 keV disk flux					
Weidenspointner *et al.* [9]		4.3±0.5	2.4±0.5	1.79	0.01%	3.80

Table 3: Comparison of the asymmetry in the galactic distribution of LMXBs seen in different surveys with that reported in the 511 keV by W08.

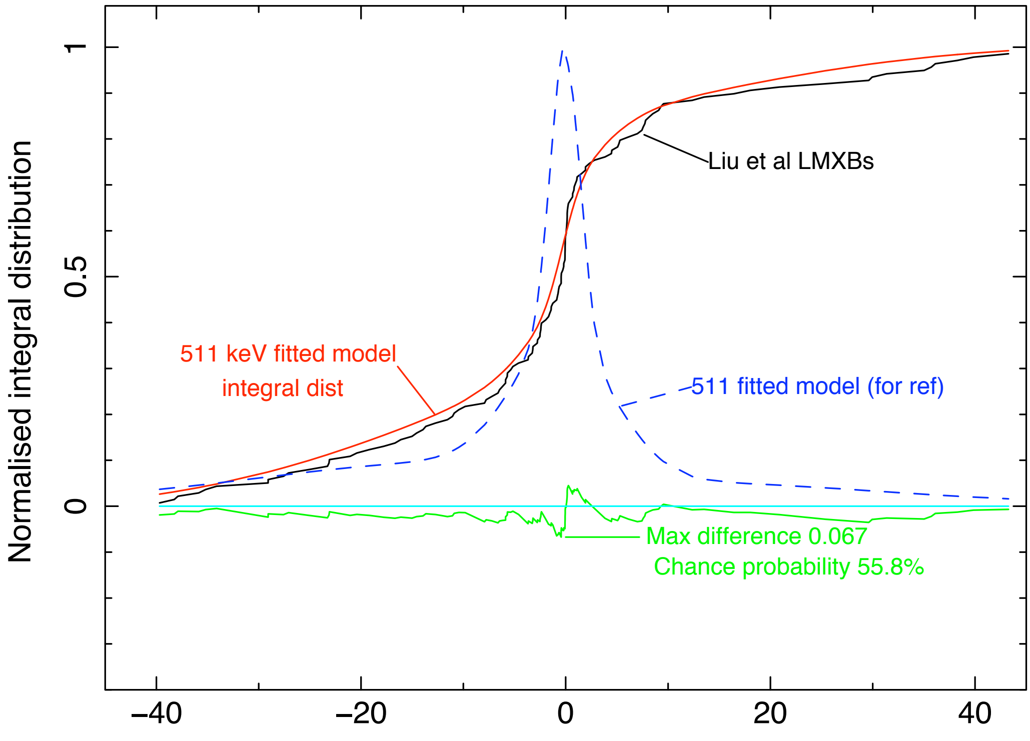

Figure 2: Kolmogorov-Smirnov comparison of the distribution of the W08 511 keV distribution model with the Liu *et al.* LMXB catalogue. Both distributions are summed $-10° < b < +10°$. Note – galactic longitude increases to the right. The difference between the two normalised integral distributions (red and black respectively) is shown in green. Its maximum absolute value of 0.067 has a high (56%) probability of occurring by chance if the underlying distribution of LMXBs were the identical to that of the 511 keV emission. Thus the data are consistent with the two being the same.

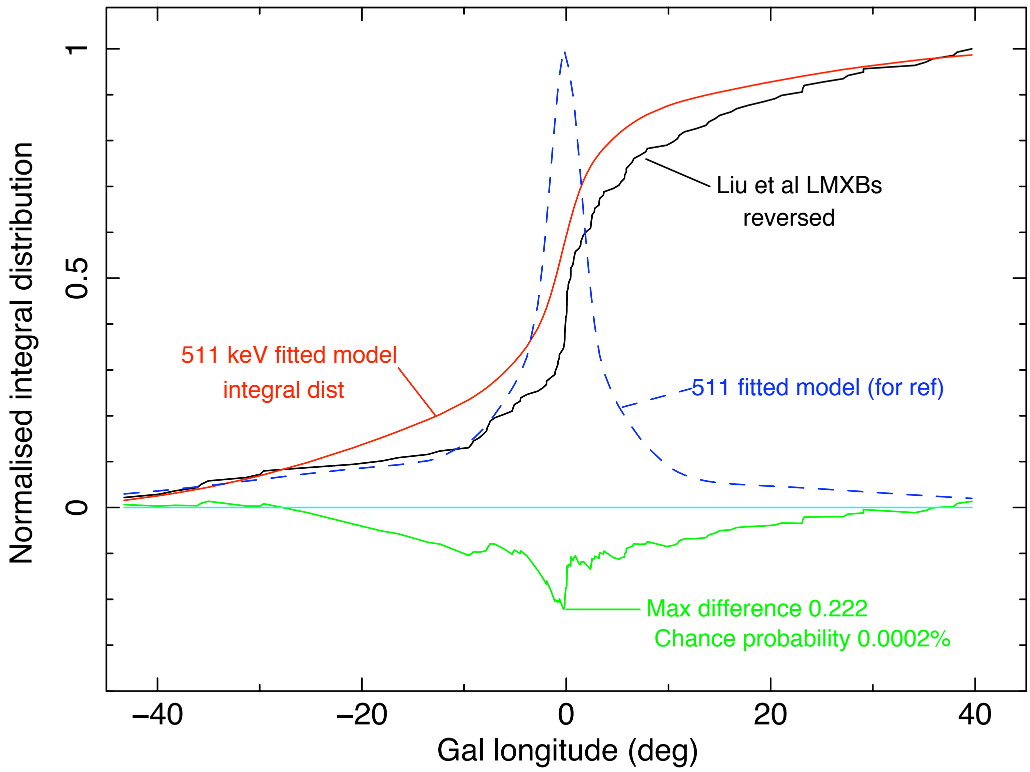

Figure 3: As Fig. 2, but with the longitude distribution of the LMXBs reversed. The Kolmogorov-Smirnov test rejects with high confidence (chance probability 2×10^{-6}) the hypothesis that the two might be the same.

In making the comparison with LMXBs we are also now in a position to consider more data (Table 3). In W08 it was noted that in the third IBIS catalogue [35] there were 71 sources at negatives longitudes ($|b| < 10^{\circ}$) identified as LMXBs, compared with 26 at positive. One can consider the probability that such a uneven distribution might occur by chance if underlying distribution were really symmetric. It is given by the binomial distribution with p =0.5 and with 71 trials (*i.e.* the distribution that describes the probability of finding at least a given number of objects in one category when 71 are allocated at random to one of two categories). One finds a probability P=0.85% that such an asymmetric arrangement should arise by chance (or double that if asymmetries in either direction are considered). This is the probability of occurrence of a 2.39σ deviation in a Gaussian distribution. Preliminary results are now available from the 36 month all-sky survey with the BAT instrument on Swift [36]. We show in Table 3, the corresponding counts of LMXBs. Although they show an asymmetry in the same direction, it is much less significant. A further comparison is possible using the list of LMXBs in the catalogue of Liu *et al.* (4^{th} edition) [37]. These are LMXBs known from observations at any X-ray energy, whereas the IBIS catalogue, in which the effect was first noticed (and the BAT one) refer only to high energies (>15 keV). An asymmetry exists in the same direction and although the ratio is less extreme, because the number of sources is higher it is of similar significance to that in the IBIS data.

In view of the relatively low significance of the LMXB asymmetry, of the fact that the BAT data do not show the effect as strongly, and of the lack of any explanation of how it could be caused, we regard (and have always regarded) the deviation from symmetry in the LMXBs as merely 'interesting'. It is not nearly as significant as that of the 511 keV asymmetry (P <0.01). Nevertheless it is of interest to compare the distributions in more detail than simply comparing total flux and total number of sources on the two sides. This can be done using the Kolmogorov-Smirnov (K-S) test. Fig. 2 compares the integral distribution of the flux in the model fitted to the SPI data (summed over $|b| < 10°$) with a similar distribution using the LMXBs in the same region. We have chosen to use the Liu catalogue at it has the best statistics. The similarity is evident and according to the K-S statistic, the maximum difference between the two could easily occur by chance if the underlying distributions were identical (P =56%). By contrast, if one of the distributions were reversed (Fig. 3) the hypothesis that they are identical could be rejected with very high confidence.

It is interesting to note that the data used in Fig 2 are for the disk **and the bulge**. The implication is that a distribution like that of the LMXBs could explain even the bulge emission, wheras from a similar analysis using the IBIS catalogue sources W08 found that although explaining all the bulge emission this way could not be excluded, the existence of an addition bulge component was favoured. The LMXBs in the Liu *et al.* catalogue are more centrally peaked, probably because of better completeness in the central region, which becomes confused with lower resolution high energy instruments.

3. Searching for localized emission associated with LMXBs

No evidence has been reported for narrow 511 keV radiation from any point source. De Cesare *et al.* [38] have for searched for such sources in the IBIS data and found none. Teegarden & Watanabe [39] have examined the positions of a large number of known sources for evidence of point-like emission at 511 keV (and at other energies) using SPI, with equally negative results. In searches [40, 41] for 511 keV emission from the Sagittarius dwarf galaxy and in this case, too, no significant flux is seen. In each case the upper limits are a few $\times 10^{-4}$ photons cm^{-2}s^{-1}, or about 10% of the bulge emission.

In an exercise to see if the data are inconsistent with the hypothesis that the 511 keV emission is in fact coming from a series of localised regions surrounding the known hard X-ray LMXBs we have made a fit with such a model to all the SPI data available to 2008 August. Fig. 4 illustrates the results from such a test. The emission from each LMXB is modelled as a 1.5°(sigma) Gaussian centred at the catalogue position. We find that, taking the number of parameters into account the fit is as good as, but no better than, that with model used in W08. Thus the hypothesis cannot be either rejected or confirmed.

4. Future prospects

In order to further investigate and extend the asymmetry reported in W08, a Key Project has been accepted for INTEGRAL AO6 in which observations will be made that are optimised to observe differences between the two sides of the galactic plane. This programme is designed to determine the flux difference between two symmetric fields in the inner disk at (l, b) = ($\pm$ 25°, 0°) in a robust, and largely model-independent, way by using a special, "beam switching" (chopping)

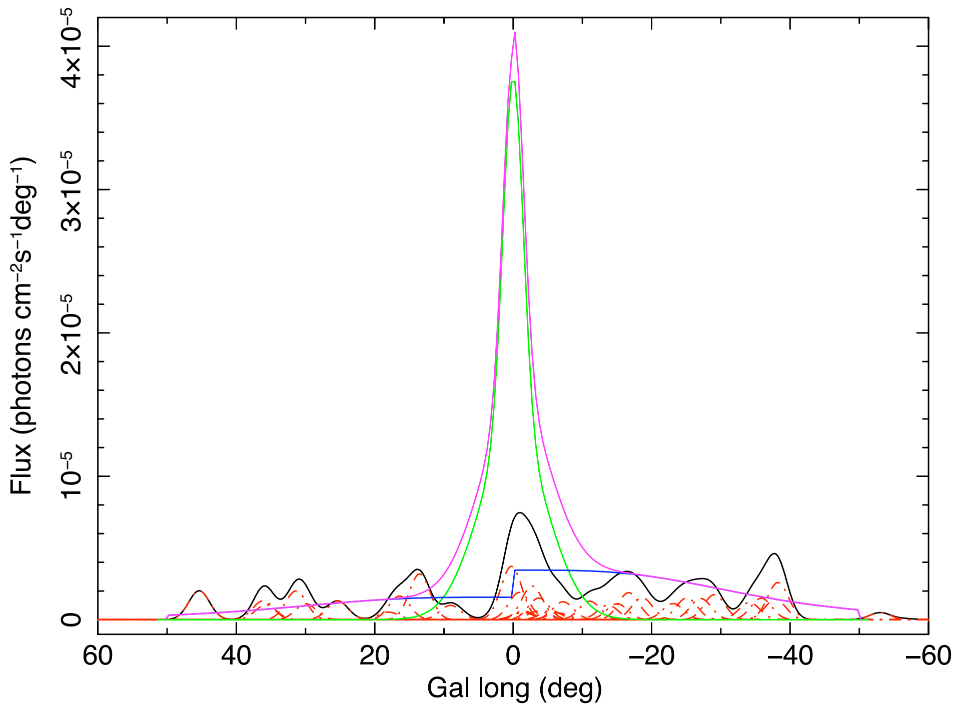

Figure 4: The longitude distribution of the W08l 511 keV model compared with that of a fit to the data with a region of emission surrounding each LMXB in the third IBIS catalogue. The bulge and asymmetric disk components of the model are shown in green and blue respectively and their sum in mauve. The red curves indicate the fitted intensity of the emission from individual LMXBs (see text) and the black one their sum.

pointing strategy (see Fig. 5). With these observations we hope and expect that SPI will continue to help us probe the question of the origin of the positrons.

References

[1] M. Leventhal, C. L. MacCallum, & P. D. Stang, *Detection of 511 keV positron annihilation radiation from the galactic center direction,* ApJ **225** (1978) L11

[2] E. Churazov et al., *Positron annihilation spectrum from the Galactic Centre region observed by SPI/INTEGRAL,* MNRAS **357** (2005) 1377

[3] G. Weidenspointner et al.*The sky distribution of positronium annihilation continuum emission measured with SPI/INTEGRAL,* A&A **450** (2006) 1013

[4] P. Jean et al., *Spectral analysis of the Galactic* e^+/e^- *annihilation emission,* A&A **445** (2006) 579

[5] J. F. Beacom, & H. Yüksel, *Stringent Constraint on Galactic Positron Production,* Physical Review Letters **97** (2006) 071102

[6] M. Cassé et al. *INTEGRAL and Light Dark Matter,* in proceedings of *5th INTEGRAL Workshop on the INTEGRAL Universe* **ESA SP-552** (2004) 65

[7] V. A. Dogiel, et al., *De-excitation C and O lines and the 511 keV annihilation line from Sgr A*,* New Astronomy Review **52** (2008) 460

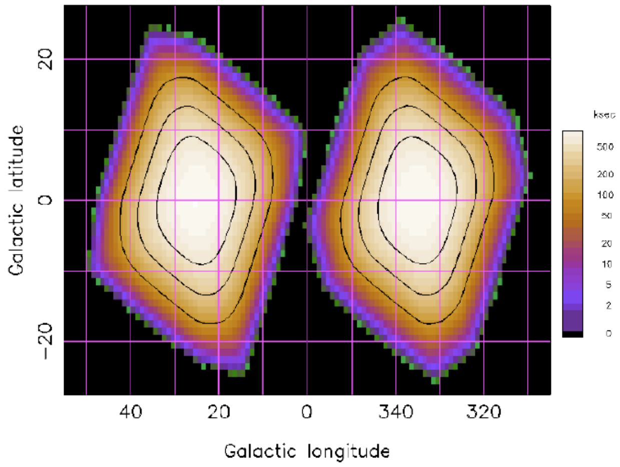

Figure 5: The effective exposure for SPI that will result from the observations being made in an AO6 Key Programme designed to examine the 511 keV disk emission and the asymmetry found in W08.

[8] D. Chernyshov, *Relaxation of Beacom and Yuksel restriction for maximum energy of annihilatingpositrons,* These proceedings (2008)

[9] G. Weidenspointner, Georg *et al.*, *An asymmetric distribution of positrons in the Galactic disk revealed by gamma-rays,* Nature **451** (2008) 159 (W08)

[10] Prantzos, N., *On the intensity and spatial morphology of the 511 keV emission in the Milky Way,* A&A **449** (2006) 869

[11] J. C. Higdon, R. E. Lingenfelter & R. E. Rothschild, *The Galactic Positron Annihilation Radiation & The Propagation of Positrons in the Interstellar Medium,* (2007) arXiv:0711.3008

[12] W. Gillard *et al.*, *Transport of positrons in the interstellar medium,* Proc. of the 6th INTEGRAL Workshop, **ESA SP-622** (2007) 65 [arXiv:astro-ph/0702158]

[13] R. Ramaty & R. E. Lingenfelter, *Gamma-ray line astronomy,* Nature **278** (1979) 127

[14] D. D. Clayton & F. Hoyle, *Gamma-Ray Lines from Novae,* ApJ **187** (1974) L101

[15] C. D. Dermer & R. J. Murphy, *Annihilation radiation in the Galaxy,* Exploring the Gamma-Ray Universe **459** (2001) 115

[16] R. E. Lingenfelter & G. J. Hueter, *Gamma-Ray Burst Emission - a Jet and Fireball Model,* American Institute of Physics Conference Series **115** (1984) 558

[17] S. Schanne *et al.* , *Hypernovae as Possible Sources of Galactic Positrons,* in proceedings of *5th INTEGRAL Workshop on the INTEGRAL Universe* **ESA SP-552** (2004) 73

[18] G. Bertone *et al.*, *Gamma-ray bursts and the origin of galactic positrons, Physics Letters B* **636** (2006) 20

[19] N. Prantzos, *Astrophysical Gamma-Ray Lines: A Probe of Stellar Nucleosynthesis and Star Formation,* 5th INTEGRAL Workshop on the INTEGRAL Universe **ESA SP-552** (2004) 15

[20] N. Guessoum, P. Jean, P., & N. Prantzos, *Microquasars as sources of positron annihilation radiation,* A&A **457** (2006) 753

[21] D. S. P. Dearborn & J. B. Blake, *On the source of the Al-26 observed in the interstellar medium,* ApJ **288** (1985) L21

[22] H. Norgaard, *Al-26 from red giants,* ApJ **236** (1980) 895

[23] P. A. Sturrock & K. B. Baker, *Positron production by pulsars,* ApJ **234** (1979) 612

[24] W. Wang, *511 keV line from millisecond pulsars in the Galactic center,* (2006) arXiv:astro-ph/0612634

[25] R. Ramaty, F. W. Stecker & D. Misra, *Low-energy cosmic ray positrons and 0.51-MeV gamma rays from the Galaxy,* J. Geophys. Res. **75** (1970) 1141

[26] D. P. Finkbeiner, & N. Weiner, *Exciting dark matter and the INTEGRAL/SPI 511keV signal,* Phys. Rev. D **76** (2007) 083519

[27] C. Boehm *et al.*, *MeV Dark Matter: Has It Been Detected?,* Physical Review Letters **92** (2004) 101301

[28] L. Titarchuk, Lev & P. Chardonnet, *The Observed Galactic Annihilation Line: Possible Signature of Accreting Small-Mass Black Holes in the Galactic Center,* ApJ **641** (2006) 293

[29] T. Totani, *A RIAF Interpretation for the Past Higher Activity of the Galactic Center Black Hole and the 511 keV Annihilation Emission,* PASJ **58** (2006) 965

[30] K. S. Cheng, D. O. Chernyshov & V. A. Dogiel, *Annihilation Emission from the Galactic Black Hole,* ApJ **645** (2006) 1138

[31] M. Pospelov & A. Ritz, *The galactic 511 keV line from electroweak scale WIMPs,* Physics Letters B **651** (2007) 208 29

[32] J-H. Huh *et al.*, *Galactic 511 keV line from MeV millicharged dark matter,* Phys. Rev. D **77** (2008) 123503

[33] M. Forbes and A. R. Zhitnitsky, *WMAP haze: Directly observing dark matter?,* Phys. Rev. D **78** (2008) 083505

[34] D. H. Oaknin & A. R. Zhitnitsky, *511 keV Photons from Color Superconducting Dark Matter,* Phys. Rev. Lett. **94** (2005) 101301

[35] A. J. Bird *et al.*, *The Third IBIS/ISGRI Soft Gamma-Ray Survey Catalog,* ApJS **170** (2007) 175

[36] J. Tueller *et al.*, These proceedings

[37] Q. Z. Liu, Q. Z., J. van Paradijs, & E. P. J. van den Heuvel, *A catalogue of low-mass X-ray binaries in the Galaxy, LMC, and SMC (Fourth edition),* A&A **469** (2007) 807

[38] G. de Cesare, *et al.*, *INTEGRAL/IBIS search of the annihilation line from the Galactic Center,* in proceedings of *35th COSPAR Scientific Assembly* **35** (2004) 2863

[39] B. J. Teegarden & K. Watanabe, *A Comprehensive Search for Gamma-Ray Lines in the First Year of Data from the INTEGRAL Spectrometer,* ApJ **646** (2006) 965

[40] B. Cordier *et al.*, *Search for a Light Dark Matter Annihilation Signal in the Sagittarius Dwarf Galaxy* in proceedings of *5th INTEGRAL Workshop on the INTEGRAL Universe* **ESA SP-552** (2004) 581

[41] J. Knödlseder *et al.* , *The all-sky distribution of 511 keV electron-positron annihilation emission,* A&A **441** (2005) 513