PROCEEDINGS OF SCIENCE

The Galactic distribution of the 511 keV e^+/e^- annihilation radiation

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We present results from the analysis of more than 10 years of data obtained with INTEGRAL/SPI on the sky distribution of the 511 keV gamma-ray line. By carefully considering a wide range of possible ways of modelling the background and by using all available good data to constrain the models we are able to place firm limits on the range of astrophysical models consistent with the data and in particular on the distribution of emission that is observed to be concentrated around the Galactic centre and Sgr A*.

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1. Introduction

One of the prime objectives of the SPI instrument on INTEGRAL is the study of the 511 keV radiation from electron-positron annihilation in the Galaxy. While the distribution of the 511 keV emission tells us directly only about where the positron annihilations take place, it provides indirect clues as to their origin. Since SPI data started becoming available there has been a series of reports of work on the morphology of the emission using datasets increasing in length from a few months to 8 years [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11]. The emission has been shown to be strongly concentrated in the 'bulge' region around the Galactic centre and there have been indications of an asymmetry, with the emission at negative Galactic longitudes being stronger that that at positive longitudes. We here report on analyses using all the available data up to 2013 April — more than 10 years of observations — and discuss what can now be said about the 511 keV distribution over the sky. We concentrate on the morphology of the line emission and spectral aspects are not addressed here. Results apply to a 6 keV wide bin centred on 511 keV, chosen to minimise effects due to line shifts or changes in instrument response.

Particular care is needed when imaging structures on scales comparable with, or larger than, the SPI field of view of $\sim 30^\circ$. Much of the pertinent information is then contained in the variations in the count rates as the INTEGRAL spacecraft executes sequences of 'dithered' pointings and as different regions of the sky are observed. Consequently accurate treatment of time variations in the detector background is crucial.

Naturally it is not possible to estimate independently the background in the 511 keV line in each detector for each pointing from the count-rates at that energy alone as the number of free parameters would equal the number of data points and all information about sky emission would be lost. Consequently assumptions have to be made and verified. It may, for example, be assumed, that for a given instrument configuration and over some chosen timescale, all of the detectors vary in the same way, retaining a characteristic 'detector pattern'. Alternatively the 511 keV background in each detector may be taken to vary in proportion to one or more 'tracers', which may be external to that detector (*e.g.* count rates from the veto shield) or internal to it (*e.g.* the rate of events at other energies, either in lines or continuum, or of events saturating the detector). More or fewer parameters may be fitted to reflect the fact that a given relationship may remain valid, for example, only within a given spacecraft orbit or over some longer interval.

Quite different approaches to background modelling can result in fits to the data that are statistically acceptable when the number of fitted parameters is taken into account, and various analyses have made different choices. It is thus important to consider the extent to which conclusions about the Galactic emission may depend on the background modelling approach adopted and we here make a first attempt to do so.

2. What has been learnt already

Prantzos *et al.* [12] have provided a thorough review of the state of our knowledge of the 511 keV emission as of 2011. The line shape and positronium-continuum fraction show that annihilation takes place after positrons have slowed down and occurs in a mixture of warm neutral and warm ionized environments. From the various studies some characteristics of the of the sky

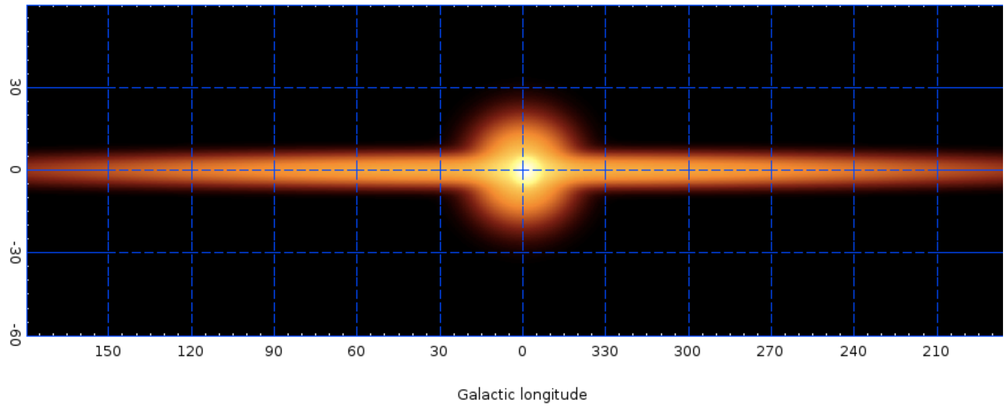

Figure 1: Image of a 'Baseline' model, **B**, consisting of the 4 components listed in Table 1, that is consistent with the data. For display purposes, here and in Fig. 2 the compact source at the nucleus has been represented as a 3-*d* Gaussian of $0.05^\circ rms$.

distribution of the emission have become clear. There is emission both from the disk and from a concentrated region around the Galactic centre (the 'bulge') and the bulge component is surprisingly strong compared with the disk emission. Estimates of the bulge/disk ratio are very model dependent but the concentration towards the Galactic centre is certainly more extreme than at any other wavelength. There appears to be an asymmetry in the distribution emission with respect to the Galactic centre, which although originally reported as stronger emission in the disk at negative Galactic longitudes compared with positive [5] now seems to be better described as an offset in the bulge emission [7, 8, 11].

Although the existence of bulge and disk components is clear, the profiles and shape of each of these is less well established. The extent and form of the disk emission and the possible existence of a broad 'halo' component are particularly uncertain.

3. A Sky Distribution Model

Fig. 1 shows a simple geometrical model consisting of the components listed in Table 1. It will be referred to here as the 'Baseline' model (**B**). Model **B** fits the observations as well as, or better than, astrophysically inspired models with components based on known distributions. With this sky model combined with one of our best-fitting background models, we find $\chi^2 - n_{dof} \sim 500$, which is acceptable ($P = 37\%$) given the large number of degrees of freedom ($n_{dof} \sim 1.2 \times 10^6$) involved[1,2] .

[1] In performing the fits reported here the amplitudes of all of the source and background components were adjusted to optimise a likelihood parameter. Given the numbers of events involved, this is essentially the same as optimising χ^2. Results are presented in terms of χ^2 as this allows the acceptability of a fit to be assessed.

[2] To find optimum positions and widths of the model components and to explore their permitted ranges it was necessary to perform repeated fits over a grid of values, which is very computer intensive. Although the intensities of all source and background model components have been reoptimised in each fit, the positions and widths of other sky model components were typically frozen at nominal values. Consequently a full marginalisation over all of the model parameters apart from those 'of interest' has not been performed and uncertainties are somewhat underestimated.

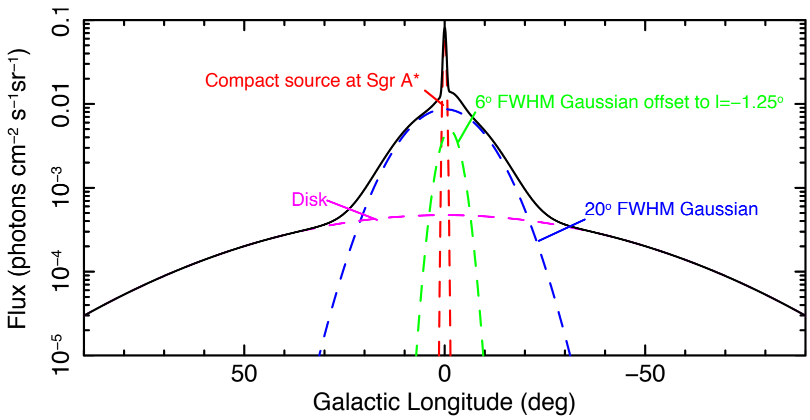

Figure 2: Cut at $b = 0$ through the model in Fig. 1.

Table 1: The components of the sky distribution model **B**. In addition, point sources at the positions of the Crab nebula and of Cyg X-1 were fitted.

Component	Type	*rms* width (deg)		Centre (deg)		Flux $\times 10^4$
		l	b	l	b	(photons cm^{-2} s^{-1})
a) Disk	2-*d* Gaussian	90	3	0	0	14
b) Wider bulge	3-*d* Gaussian	8.7	8.7	0	0	7.3
c) Narrow bulge	" "	2.5	2.5	-1.15	-0.25	2.8
d) Central component	Compact	0	0	-0.06	-0.05	1.2

3.1 A Central Component ?

It is notable that the best-fit geometric models of the bulge emission include a central cusp, represented in the model **B** by a point source. The position of the point source has been taken as that of Sgr A*, but with the $\sim 3^\circ$ resolution of the SPI instrument this is indistinguishable from $l, b = (0,0)$, the separation being only 0.07°. Fig. 3 shows the χ^2 contours as the location of this component is varied.

With this resolution it is of course difficult to be certain just how compact this component must be. Fig. 4 shows how χ^2 varies when the point source is replaced by a 3-dimensional Gaussian distribution of different widths. It appears that the central component has a characteristic scale no more than a few hundred pc.

3.2 The Bulge Offset

We confirm the conclusion that the observed asymmetry is better represented as an offset of the bulge emission than by the somewhat artificial splitting of the disk emission into two imbalanced halves with an associated diskontinuity at $l = 0$ used in the analysis of [5].

We have investigated the extent to which the data indicate which of the components of our geometric model are offset. Offsetting the widest bulge component ((b) in Table 1) improves the fit very little but offsetting the narrower one (c) leads to a significant improvement as seen in Fig. 3. It

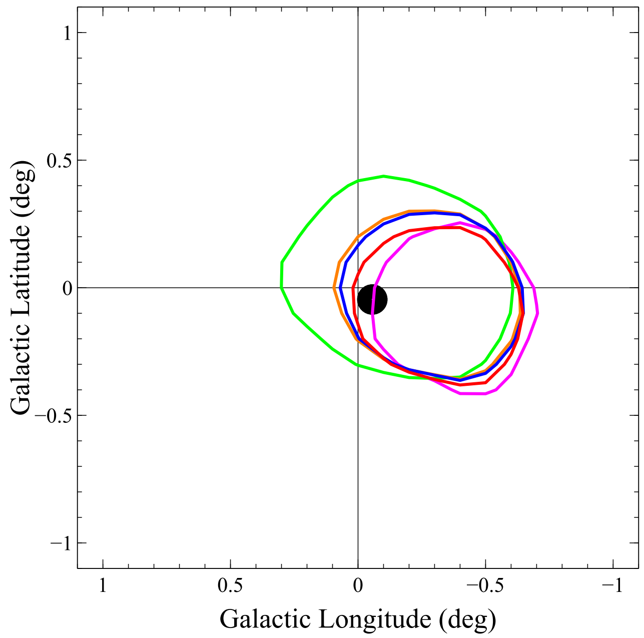

Figure 3: The best fit position for the central compact component. Contours at $\chi^2_{min} + 4.6$ are shown for 4 different background models (see §5). The spot marks the position of Sgr A*.

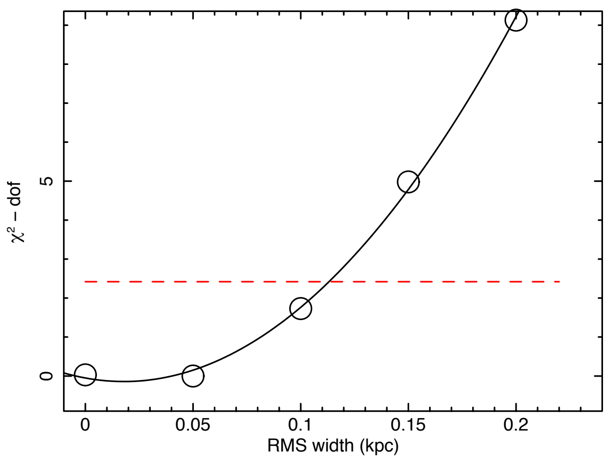

Figure 4: The effect on the quality of fit of varying the width of the compact component of model **B**. The dashed line indicates the 68% confidence level.

has already been seen that there is only marginal evidence for an offset of the compact component. Solutions in which all three bulge components are offset together are all inferior.

The similarity of the best position for the offset bulge component to that of 1E1740−2942 is intriguing. This source is the strongest hard X-ray source in the region and is still sometimes referred to as 'the great annihilator' following the apparent detection of a transient spectral feature close to 511 keV during observations with SIGMA [13, 14]. Given that there are conflicting upper limits at around the time of the SIGMA observations [15, 16] and that no repeat of the phenomenon has been reported, the name may be misleading. In any case we have searched for indications in our data of a compact 511 keV source at the position of 1E1740−294 and found none. Thus it

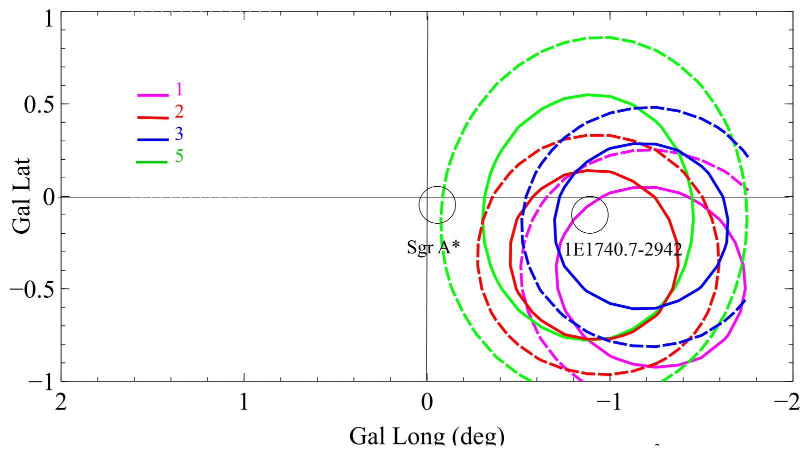

Figure 5: Error regions for the position of the narrow bulge component, other components being fixed at the values in Table 1. Contours for $\chi^2_{min} + 2.3$ and $+4.6$, corresponding to 68% and 90% confidence are shown as continuous and dashed lines respectively for 4 different background models (see §5).

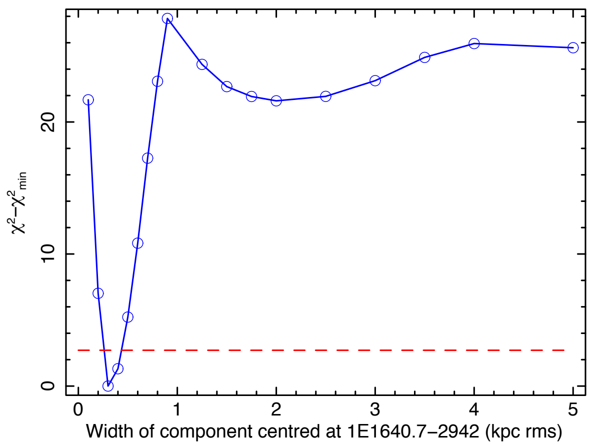

Figure 6: Investigation of the best fit size for a 3-d Gaussian component centred at the position of 1E1740−2942. The dashed line corresponds to $\chi^2 - \chi^2_{min} = 2.7$ (90% confidence for 1 parameter of interest).

seems likely that the similarity is a coincidence.

3.3 The Disk

Despite the large amount of SPI data now available, the form of the disk component remains poorly constrained. Quite different models give fits of comparable quality. Furthermore, as will be noted in §5, unlike the situation with the bulge emission, use of different background modelling approaches leads to different conclusions about the form of the emission.

With most of the background models investigated, an oblate Gaussian representation of the disk in **B** is found to have an *rms* latitude extent of a few degrees, typically $\sim 3^\circ$. The longitude extent found, though varies widely, from 30–100°. We note the assumed extent has a direct impact on the estimated flux from this component and hence on the bulge-to-disk ratio.

We have investigated models for the disk emission based on various astrophysical distributions. Among those that, when combined with a bulge model similar to that in **B**, provide an adequate fit to the data are: the narrower of the Fermi Galactic background models [3] , the Cordes and Lazio NE2001 Galactic Free Electron Density Model [17] and the TC93 model that it supersedes. None however provides a fit that is actually superior to the simple Gaussian representation.

4. Dark Matter Profiles

No known objects have a distribution as strongly concentrated around the centre of the Galaxy as the 511 keV emission. While we do not wish to overstate its significance, one intriguing possibility is worth consideration. A number of suggested origins for the positrons responsible for the 511 keV emission link them to Dark Matter. Dark Matter (DM) distributions, both those deduced from stellar motions and those resulting from simulations, have various degrees of 'cusping' around the Galactic centre. We may distinguish two classes of theories linking the positrons to DM. In one the DM undergoes spontaneous decays and so the positron production is simply proportional to the DM density (ρ^n with $n = 1$). In the other either excitation or annihilation takes place in interactions between DM particles, resulting in positron production proportional to the square of the density ($n = 2$).

We find that the well known Navarro, Frenk and White (NFW) Dark Matter distribution [18]

$$\rho(r) = \frac{\rho_0}{(r/R)^\gamma[1+(r/R)^\alpha]^{(\beta-\gamma)/\alpha}}, \tag{4.1}$$

with $\alpha = 1$, $\beta = 3$, $\gamma = 1$, $R = 20$ kpc, can replace all three bulges components in **B** and provide a remarkably good description of the form of the bulge emission when the index n is set to 2. In fact if a continuum of values of n including non-integer ones is considered the optimum fit is obtained with $n = 2.15 \pm 0.15$ (90% confidence), as seen in Fig. 7.

Although Eqn. 4.1 implies a distribution symmetric about the Galactic centre and so is not consistent with an offset bulge emission, it has been noted in a different context that simulations often result in offsets between the DM peak and the dynamical centre of the Galaxy of up to several hundred pc [19].

5. The Effect of the Assumed Background Model

We have investigated the extent to which the results found here are dependent on the choice of background model. As examples, in Figs 3 and 5 results are shown for different background modelling approaches. Briefly they are as follows:

1 (Magenta) A fixed detector background 'pattern' for each instrument configuration, determined from 'off' high latitude pointings away from known sources

[3] Available from `http://fermi.gsfc.nasa.gov/ssc/data`. The version of the diffuse model we used is gll.iem.v02. A description of this model is available at `http://fermi.gsfc.nasa.gov/ssc/data/access/lat/ring_for_FSSC_final4.pdf`.

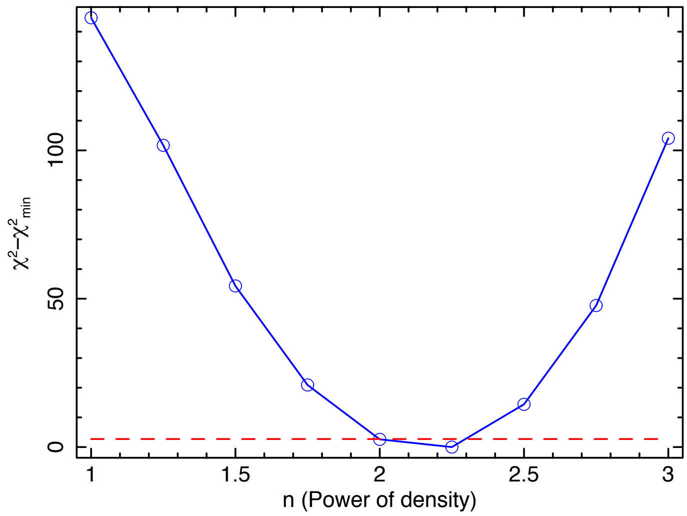

Figure 7: Fitting the bulge 511 keV flux with the form expected from Dark Matter, with emission proportional to ρ^n where ρ is the density, assumed to be distributed according to an NFW profile. The dashed line corresponds to $\chi^2 - \chi^2_{min} = 2.7$ (90% confidence for 1 parameter of interest).

2-4 (Red, Blue, Orange) Background based on various combinations of tracers with scaling factors and with parameters covering different periods and numbers of detectors. Results for the third of these combinations is not shown in Fig. 5 to reduce confusion, but results are similar to the other two.

5 (Green) Similar to 1, but using multiple pattern components, also using information from a broader energy range, and allowing for detector degradation.

It is seen that although the size of the permitted region may change somewhat, for parameters describing models for the bulge emission most of the allowed region is in common to different analysis methods and the general conclusions are independent of the approach. As noted in §3.3, the same is not true of the much more extended disk emission. This is presumably due to the fact that different parts of the disk tend to be observed at widely separated times because of the spacecraft sun constraints, combined with the fact that information about the relative count-rates across the detector plane contribute little information to observations of large scale diffuse emission.

6. Discussion

The information provided by SPI on the distribution of the 511 keV flux from the bulge region is now quite constraining. Obviously the 511 keV gamma-rays indicate the site of the annihilation of the positrons, not that of their generation. The fact that positrons are created at energies of (at least) $\sim$ MeV but the annihilation line is narrow means that they must travel far enough to slow to energies of $\sim$ keV or less. It is conceivable that positrons produced over a larger volume annihilate preferentially in a compact region, perhaps guided there by magnetic fields – see for example [12, 20]. However, it seems more likely that diffusion will **broaden** the distribution of the emission compared with that of the positron birth sites, in which case their generation in a very compact region must be explained.

The similarity between the observed form of the bulge emission and the expected shape from positrons produced by a two-body process between Dark Matter particles following an NFW distribution is tantalising. Unless or until the nature of the Dark Matter is identified it will be difficult either to exclude, or to prove, explanations for the origin of the Galactic centre positrons based on such an hypothesis.

The disk emission, on the other hand, is both less well defined by the observations and easier to explain. Although the 511 keV luminosity of the disk is rather uncertain because its extent is poorly known, it appears to be compatible with the annihilation of positrons produced in radioactive decays that are known to occur.

Work on improving the SPI background modelling is continuing, with the prospect of reducing the uncertainties in the observations of the very diffuse disk emission. Meanwhile, the instrument is continuing to function well and more data at 511 keV is collected incidentally during every observation made for other purposes.

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