PROCEEDINGS OF SCIENCE

The 511 keV sky as seen by INTEGRAL/SPI, CGRO/OSSE, SMM/GRS and WIND/TGRS combined

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Over more than 30 years three space-borne spectrometers have accumulated a wealth of data on the angular and spectral distribution of the 511 keV Galactic e^+/e^- annihilation radiation : GRS on the Solar Maximum Mission monitored the 511 keV line from the Galactic Center region in the eighties, the first maps of the inner Galaxy were produced by OSSE/CGRO in the nineties, and since 2002 SPI/INTEGRAL has been performing high resolution imaging spectroscopy over the entire sky. Until now our understanding of the 511 keV emission, and hence of the origin of the Galactic positrons, has been largely based on the analysis of the data-sets independently. We present an analysis of the combined data, constraining the spatial distributions of the galactic e^+/e^- annihilation radiation by fitting the same models to the SPI data and to those from other instruments.

An INTEGRAL view of the high-energy sky (the first 10 years) - 9th INTEGRAL Workshop and celebration of the 10th anniversary of the launch
15-19 October 2012
Bibliotheque Nationale de France, Paris, France

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†Much of the work decried here was carried out while the author was at the University of Maryland and the Goddard Space Flight Center.

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1. Introduction

Early attempts to understand measurements of the 511 keV line radiation resulting from positron annihilation in the galaxy were confused by the different fields of view of the various instruments used, at one point leading to the erroneous conclusion that the emission was variable and hence must originate in a compact source, *e.g.* [1]. We here show how one can take advantage of the different fields of view and capabilities of instruments launched as much as 30 years ago to complement the data on the galactic distribution of the 511 keV radiation being gathered by INTEGRAL's SPI spectrometer.

In Table 1 we compare the characteristics of SPI with those of the various instruments from which archival data has been used. SPI obtains information preferentially on the $\sim 3^\circ$ angular scale associated with the mask pattern, but also to some extent on a larger scale through using the anticoincidence shield as a collimator to define the field of view. The latter is sometimes referred to as 'light-bucket' mode, but in practice in the type of analysis reported here the data in the two modes are not distinguished. Instead a sky model is sought that is most consistent with the data, given a response matrix that fully describes both aspects of the instrument.

The same models have here been fitted both to the data from SPI alone, now using 9 years of data, so considerably more than for previous reports, and (separately) to those from all 3 of the other instruments, combined. We then consider which models are consistent with both datasets, noting that the archival data provide tighter constraints on the structure of the emission on large angular scales.

Two key aspects that have been examined are (i) the report by Weidenspointner *et al.* [2] (W08 below) that the 511 keV emission from the galaxy is not symmetric about $l = 0$, with the emission at negative galactic longitudes being stronger than that at positive, and (ii) the indications from various measurements that there is an extended, 'spherical' component to the emission.

Table 1: default

Instrument	Operational	Mode of operation	Angular scale
INTEGRAL SPI	2002 – date	Imaging	$\sim 3^\circ$(mask); $\sim 16^\circ$ (collimator)
WIND TGRS	1994 – 1996	Scanning occultor	$90^\circ \times 6^\circ$
CGRO OSSE	1991 – 2000	Rocking collimators	$11.4^\circ \times 3.8^\circ$
SMM GRS	1980 – 1989	Annual modulation	130°

2. The range of models considered

The work described here has concentrated on testing models for consistency with the observed data rather than reconstruction of images that may be difficult to interpret because of uncertainty about the significance of features observed. Because terminologies used are sometimes different, we first define the model components that we have considered.

One of the surprises in observations of the 511 keV line emission has been its high degree of concentration towards the galactic centre. Previous work (*e.g.*W08) has led us to describe the central emission as a combination of two components that we term the inner ($\sim 1^\circ$ scale) and outer ($\sim 10^\circ$ scale) 'bulge' components. In each case the emissivity is taken to be a Gaussian function of the distance from the galactic centre. In the work described here width of these components has not been re-optimised but the values of 0.5 and 0.08 kpc (1σ, equivalent to 3.5°and 0.5°) respectively found in earlier analyses have been adopted.

Many of the possible origins of the positrons are associated with objects that occur largely in the galactic disk - an example is that some positrons must be produced in the decay chains of ^{56}Ni, ^{44}Ti, and ^{26}Al produced in recent (< a few My) supernovae (*e.g.*[3]). Although unexpectedly weak in comparison to the bulge emission, 511 keV radiation is detectable from the plane of the galaxy. For this disc component we have tried various distributions as described below, in particular a projection onto the sky of a general emissivity distribution with a central 'hole' as formulated by Robin *et al.* [4] for a young disk

$$\rho(R) \propto \exp\left[-\frac{1}{R_+^2}\left(x^2+y^2+\frac{z^2}{\varepsilon^2}\right)\right] - \exp\left[-\frac{1}{R_-^2}\left(x^2+y^2+\frac{z^2}{\varepsilon^2}\right)\right] \tag{2.1}$$

but with various combinations of parameters R_+, R_-, ε.

Finally, in view of indications of very diffuse 511 keV emission extending out of the galactic plane, we consider the evidence for a spherical halo, for which we adopt the density distribution similar to that suggested by OSSE observations [5]:

$$\rho(R) \propto \left(\frac{R}{R_{scale}}\right)^{-\frac{7}{8}} \exp\left[-\left(\frac{R}{R_{scale}}\right)^{\frac{1}{4}}\right] \tag{2.2}$$

with R_{scale} = 1.2 pc and with the central peak clipped at $\rho(0.3\text{pc})$.

In addition we consider different ways in which an asymmetry between negative and positive galactic longitudes could be represented within the context of such modelling. In (W08) Weidenspointner *et al.*described the asymmetry that they found in terms of a disk model with different scaling factors at negative and positive longitudes. The abrupt transition that this implies at $l = 0$ is obviously physically unrealistic, so we have considered alternative disk distributions of the form

$$D(l,b) \propto \left(A_- + \frac{A_+ - A_-}{1+\exp(-l/w)}\right) R(l,b) \tag{2.3}$$

where $R(l,b)$ is the distribution expected for a Robin disk of the form in Eqn. 2.1 and w is a measure of the width of the sigmoid function defining the transition.

In all cases the scaling factor for all of the components considered were fitted, optimising likelihood (SPI) or χ^2 (OSSE/SMM/TGRS). The sealing factors were not constrained to be the same in the two cases, but in practice similar values were found.

3. The disk emission

Using the map of the ^{26}Al emission from Comptel observations [6] as a model for the 511 keV disk emission, together with a 2 Gaussian bulge model as described above, centered at $(l,b) = 0,0$ does not provide a good match to the SPI data. It is known that not all of the structure in the Comptel map is real, so some potential surrogate maps [7], known to be consistent with the Comptel data but better defined, were tried as representations of the disk component. None of the fits to the SPI data alone was as good as that with versions of a Robin disk with a rather large extent in latitude (*e.g.* $R_+ = 3.9$ kpc, $R_- = 3.15$ kpc, $\varepsilon = 0.29$). Fits to the OSSE/SMM/TGRS data were consistent with this. Thin disks did not provide adequate fits to either dataset. A full exploration of the range of possibilities is underway and will be reported elsewhere.

4. Symmetry?

The finding by (W08) of an asymmetry in the 511 keV emission was unexpected. Subsequent work also using SPI data failed to find evidence to support this finding [8] or saw only a low significance effect that was described in terms of a bulge offset rather than a disk asymmetry [9]. There are indications that the difference in the conclusions arises from different ways of handling the instrument background, with some approaches being intrinsically less sensitive to any asymmetry present [10]. Further refinements in modelling the SPI background in the region of the 511 keV line are ongoing but we here continue to use that adopted in (W08), believing that by modelling the background using a large number of fitted parameters reduces the probability of introducing spurious effects, even if the significance of detection of real features is somewhat reduced, and noting that the extra parameters seem to be statistically justified [10].

With the larger dataset now available an asymmetry is detected with a significance of approximately 5σ, with the emission at negative galactic longitudes being brighter than that at positive. It can be described, as was found by W08, by applying different scaling factors to the negative and positive longitude halves of a map corresponding to a thick Robin disk. As noted above, the discontinuity in surface brightness that this implies at $l = 0$ cannot be physical. However we find that adopting the smoother transition using a model of the form of Eqn. 2.3 does not improve the fit, the optimum fit to the SPI data being obtained with $w \to 0$.

Consequently we have examined whether the asymmetry may be better described in terms of a displacement in l of the bulge. One can consider the possibility that either it is the more compact ('narrow', $\sim 1^\circ$) component is displaced, or the 'wide' one, or both together. The black lines in Fig. 1 show contours of likelihood when fitting to SPI data a model consisting of a symmetric disc as a function of the displacements of the two bulge components. That neither component is displaced is excluded at 4.8σ, and although the best fit involves both components being displaced a solution with only the wider component offset (by 1.4°) and the narrow one remaining at $l = 0$ is consistent with the data, falling within the 1σ contour.

The solid coloured contours in 1 show the results of fitting the same range of models to the OSSE/SMM/TGRS data. Again a hypothesis involving a symmetric disk and no displacement is excluded (at $\sim 3\sigma$) and although displacements of the wider component appear to be marginally preferred, solutions suggested by the SPI analysis fall within the 1σ contour.

Forming a joint likelihood function for the two datasets leads to the range of solutions defined by the dashed contours.

The fits obtained by displacing the bulge components are, however, not significantly better than those with an asymmetric disk, so the two possibilities cannot be distinguished. Furthermore other models cannot be excluded – for example adding an additional component (which has to be

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extended with a size > 2°, not a point source) at around $(l,b) = -1°, 0°$ to a symmetric disk and bulge also gives an adequate description of the data.

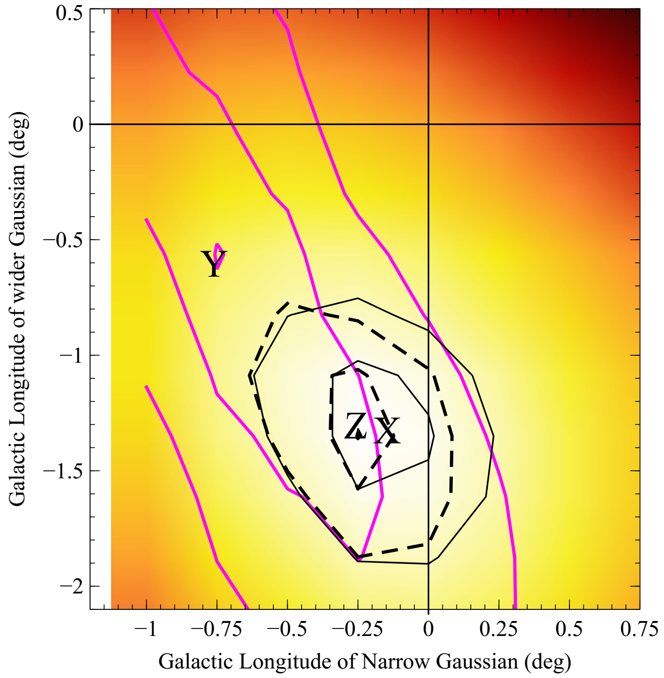

Figure 1: The effect of displacing the two bulge components with a model comprising bulge and symmetric Robin disk. Contours are at 1 and 2 σ. Black solid line SPI data alone (X indicates the best fit); coloured solid line OSSE/SMM/TGRS data alone (Y indicates the best fit); dashed line combined (with Z the best fit). Galactic longitude increases up and to the right.

5. An extended halo ?

Fig. 2 addresses the issue of whether there could be a very extended spheroidal component to the 511 keV emission, in addition to the bulge and disk components. Although the SPI data are best fitted by models without such a component, because of the relative insensitivity of the measurements to large scale structures, the presence of even a large flux from such a component is not strongly excluded. On the other hand, the *absence* of such diffuse emission appears to be inconsistent with the OSSE/SMM/TGRS dataset.

The presence of such an extended component at the implied level would have important implications. Consideration of the joint probability suggests a flux corresponding to about 1.4×10^{43} annihilations per second, doubling the estimate of the total annihilation rate within the galaxy. In this context, it is notable that when the same model components are fitted to either the SPI data or to those from the other three instruments, very similar fluxes are obtained

6. Conclusions

The present paper represents a status report on a continuing activity, by a widely dispersed group of people. The objective is to provide an analysis of all of the available Integral/SPI 511 keV data, which now spans 10 years, using a variety of different software systems and background modelling techniques in order to gain confidence in the results obtained and at the same time taking into account the substantial body of archival data from other instruments. The results presented here confirm the existence of an asymmetry, while leaving unresolved questions about the form that it takes, and indicate the presence of an extended halo in addition to disk and bulge components.

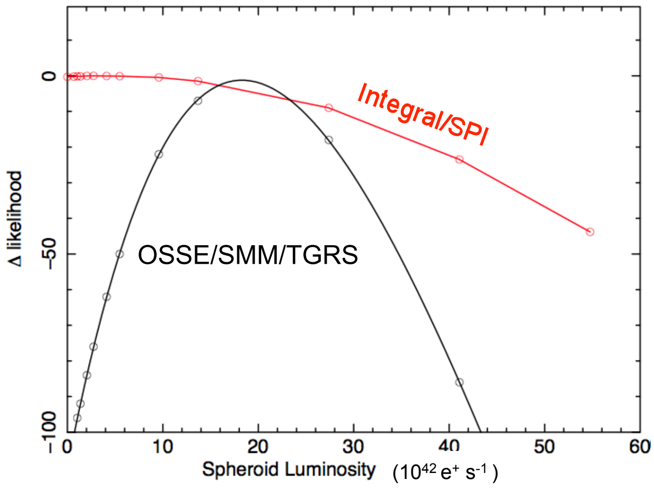

Figure 2: The effect on likelihood of adding an extended spheroidal component to a model consisting of narrow and wide Gaussian components at (0,0) and a Robin disk.

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