SF2A 2006
D. Barret, F. Casoli, T. Contini, G. Lagache, A. Lecavelier, and L. Pagani (eds)

NEW CLUES TO THE ORIGIN OF GALACTIC POSITRONS

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Abstract. The imaging spectrometer SPI on board ESA's INTEGRAL observatory provides us with an unprecedented view of positron annihilation in our Galaxy. The first sky maps in the 511 keV annihilation line and in the positronium (Ps) continuum from SPI showed a puzzling concentration of annihilation radiation in the Galactic bulge region; detailed spectroscopy with SPI showed that positrons annihilate there in a warm interstellar medium. By now, more than twice as many INTEGRAL observations are available, offering new clues to the origin of Galactic positrons. We present the current status of our analyses of this augmented data set. We now detect significant emission from outside the Galactic bulge region. The 511 keV line is clearly detected from the Galactic disk, allowing us to perform the first spectroscopic study of this emission with SPI. In addition, there is a tantalizing hint at possible halo-like emission. The available data do not yet permit to discern whether the emission around the bulge region originates from a halo-like component or from a disk component that is very extended in latitude.

1 Introduction

The detection of 511 keV positron annihilation line emission from the central region of our Galaxy was one of the early and important successes of gamma-ray astronomy (Leventhal, MacCallum, & Stang(1978)). Although positron annihilation gives rise to the strongest gamma-ray line signal from our Galaxy, three decades of dedicated observational and theoretical effort have fallen short of unveiling the origin of Galactic positrons. A large variety of potential astrophysical and exotic positron sources have been proposed (see e.g. Weidenspointner et al.(2006b)), among them the decay of radioactive nuclei expelled by supernovae, compact objects, or light dark matter.

Investigations of the sky distribution of the annihilation radiation promise to provide clues for the identification of the source(s) of positrons in our Galaxy. Positrons may travel from their birth places before annihilating, however, recent theoretical work suggests that positron diffusion is limited (Jean et al.(2006a), Gillard et al.(2006)). Thus the Galactic distribution of annihilation radiation can be expected to resemble that of the positron sources. Additional insight into the origin, propagation, and annihilation of positrons can be obtained from high-resolution spectroscopy. The detailed shape of the annihilation line and the ratio of the fluxes in the line and the Ps continuum depend on the physical conditions of the interstellar medium in which positrons annihilate (see e.g. Guessoum, Jean, & Gillard(2005)).

BASED ON OBSERVATIONS WITH INTEGRAL, AN ESA PROJECT WITH INSTRUMENTS AND SCIENCE DATA CENTRE FUNDED BY ESA MEMBER STATES (ESPECIALLY THE PI COUNTRIES: DENMARK, FRANCE, GERMANY, ITALY, SWITZERLAND, SPAIN), CZECH REPUBLIC AND POLAND, AND WITH THE PARTICIPATION OF RUSSIA AND THE USA.

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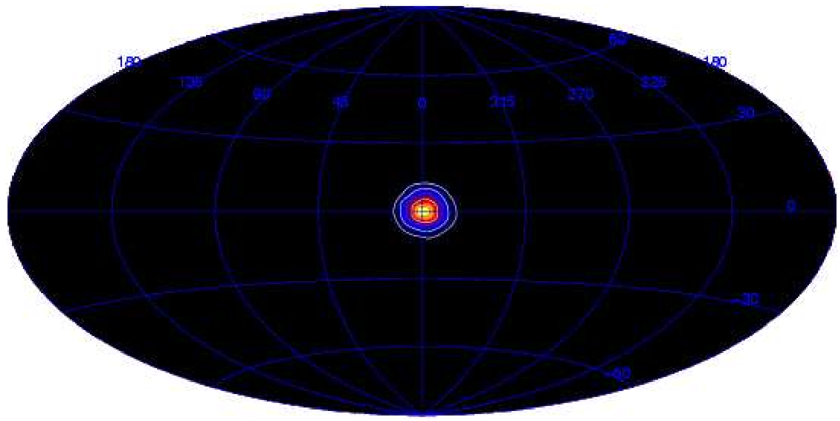


Fig. 1. An MREM sky map of the 511 keV positron annihilation line emission. The contours indicate intensity levels of 10^{-2}, 10^{-3}, and 10^{-4} ph cm^{-2} s^{-1}. Details are given in the text.

In this contribution, we present the current status of our studies of the large-scale distribution of Galactic 511 keV annihilation line radiation and its spectrum using more than 2 years of observations with the spectrometer SPI (more detailed accounts can be found in Weidenspointner et al.(2006b) and Jean et al.(2006b), respectively).

2 Instrument and Data Analysis

The results presented here are based on a data set that comprises more than twice as many observations as that we used in our studies after the first year of the mission (see Knödlseder et al.(2005), Jean et al.(2006a), and Weidenspointner et al.(2006a)). Specifically, we have used the April 20, 2006 public INTEGRAL data release (i.e. three-day orbital revolutions 16-269, 277, 278, 283-285). These public data were supplemented by instrument team observations of the Galactic center region and of the Galactic plane and by recent private observations of SNR 1006, Cen X-4, and Sco X-1 up to revolution 423. The observations were taken during the epoch November 23, 2002 through April 1, 2006. During this time a few very strong (notably during October 2003 and September 2005), and several smaller, solar flares occurred. These resulted in strong transient enhancements of the instrumental background at 511 keV. These exceptional periods were removed, resulting in a cleaned data set that consists of about 18000 pointings with a combined live time of about 4×10^7 s. To analyze this augmented data set we employed the same tools and followed the same procedures as for the analyses of the observations of the first year of the mission.

3 Results

3.1 Imaging

To obtain a model independent sky map of the 511 keV positron annihilation line radiation, we employed the Multi-Resolution Expectation Maximization (MREM) algorithm described in Knödlseder et al.(2006). The resulting sky map is depicted in Fig. 1. As in earlier SPI analyses of the positron annihilation line (Knödlseder et al.(2005)) and the Ps continuum (Weidenspointner et al.(2006a)), the only prominent 511 keV line signal is that seen from the central region of our Galaxy. Any emission from other sky regions is much fainter. As with the first year observations, we find again that the centroid of the emission is close to the Galactic center.

3.2 Model Fitting

A more quantitative approach for studying the Galactic distribution of the observed extended line emission is model fitting. In the present work, our focus is on investigating whether there is 511 keV line emission outside the central region of the Galaxy. In particular, we are trying to characterize the emission from the Galactic disk, and to assess whether there is evidence for emission from a halo component. In the first year data, disk

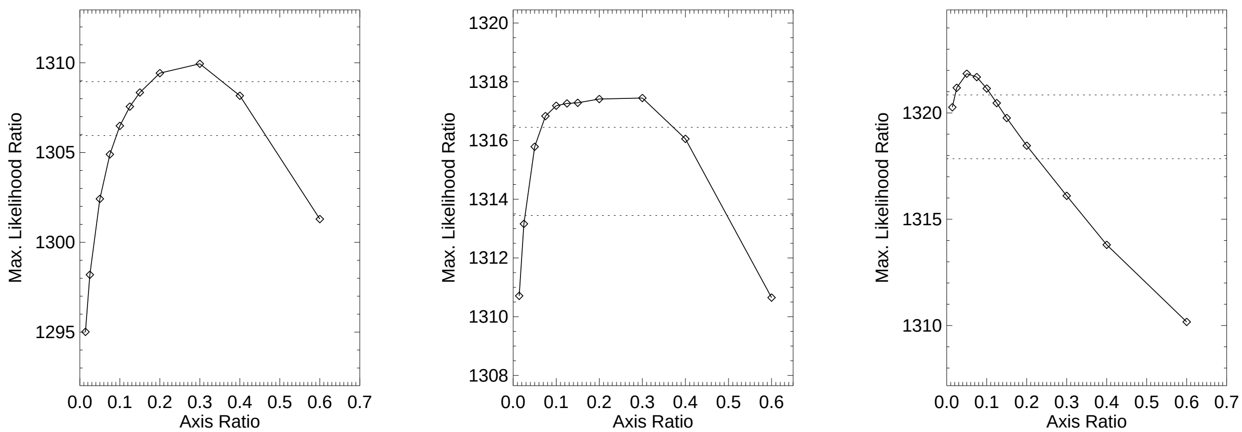


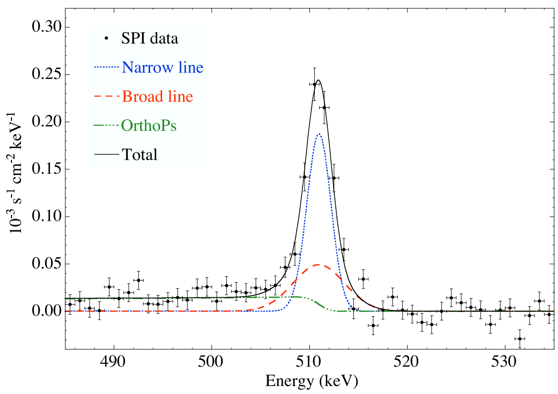
Fig. 2. Left panel: the variation of the maximum likelihood ratio λ when fitting the data with the Robin et al.(2003) young disk plus an ellipsoidal model (FWHM $\Gamma_l = 6.5°$ and $\Gamma_b = 6.0°$) of the bulge emission. Center panel: as left panel, except that the bulge emission is modelled by a combination of 0–0.5 kpc and 0.5–1.5 kpc homogeneous shells. Right panel: as left and center panels, except that the emission from the central region of the Galaxy is described by the stellar halo model of Robin et al.(2003). The dashed lines indicate decreases of λ by 1 and 4, corresponding to 1 and 2σ confidence levels for 1 degree of freedom.

emission was already marginally detected, while a stellar halo component (comprising emission peaking at the Galactic center and fainter emission extending far beyond the bulge region) could not yet be distinguished from pure bulge models.

In order to investigate the possible existence of faint and extended emission from outside the central region of the Galaxy we fitted simple and flexible models for bulge and halo emissions in the absence or presence of simple disk models. The bulge and halos emissions were represented by nested spherical shells of homogeneous emissivity, centered at the Galactic center. The disk emission was described either by the young (0–0.15 Gyr) or the old (7–10 Gyr) stellar disk models as derived by Robin et al.(2003). We then detect significant 511 keV line emission from outside the bulge region of the Galaxy. A pure bulge model cannot explain the observations. Adding a halo component (i.e. shells extending farther from the Galactic center) and/or a disk model significantly improves the fits. The disk models are favoured over the halo models since either disk model improves the fit more than additional shell/halo components.

We then investigated other characterizations of the bulge and disk emission. We find, for example, that models for the stellar bar derived from IR observations provide rather poor descriptions of the emission from the bulge region; it therefore appears that the distribution of the 511 keV line emission does not follow the stellar bulge. The stellar halo model of Robin et al.(2003), however, provides a very good fit of the data. It is too early to conclude that indeed halo emission around the Galactic center region exists. The good agreement between data and stellar halo model may mainly be due to the fact that it models well the peaked emission at the Galactic center. The existence of a sharp peak in the emission is also hinted at by the good fit of the data that can be obtained by describing the bulge emission with two Gaussian distributions, centered at the Galactic center, with FWHM of about 2° and 8°.

Our final step to date in investigating whether there is 511 keV line emission outside the central region of the Galaxy, and whether it can be uniquely described by rather simple models, was to vary the axis ratio parameter in the Robin et al.(2003) young and old disk models. Combined with either a two-shell description or with an ellipsoidal (FWHM $\Gamma_l = 6.5°$ and $\Gamma_b = 6.0°$) description of the bulge emission, or with the stellar halo model by Robin et al.(2003). As an example, for the young disk the variation of the maximum likelihood ratio λ with the axis ratio ϵ for the three descriptions of the emission from the central region of the Galaxy are depicted in Fig. 2. The results for the old stellar disk are similar. We note that the axis ratios for the Robin et al.(2003) young (0–0.15 Gyr) and old (7–10 Gyr) stellar disks are 0.014 and 0.0791, respectively. For both bulge models, the preferred axis ratio is about 0.3, much larger than Robin et al.'s young disk value, in particular. The uncertainty is, however, rather large. For the stellar halo, the preferred value of ϵ is similar to those for the Robin et al.(2003) stellar disks, and the uncertainty is much smaller. These results clearly demonstrate that



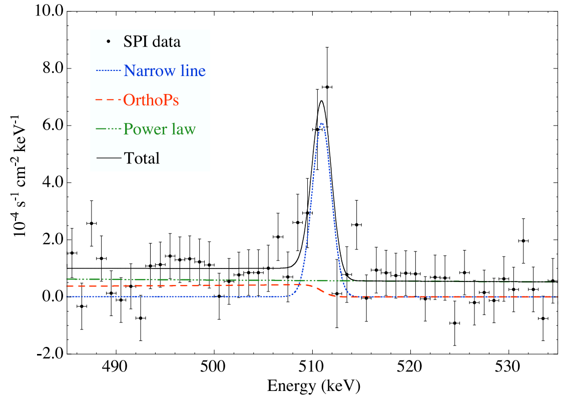


Fig. 3. The spectra of emission from the Galactic bulge (left panel) and the Galactic disk (right panel). Details are given in the text.

there is faint, extended emission around the central region of the Galaxy, but that with the current data it is impossible to decide whether this emission is due to a halo-like component, or a disk very extended in latitude.

3.3 Spectroscopy

To obtain spectra of the annihilation radiation from the Galactic bulge and disk we had to chose specific models for the sky distribution of these emission components. We modelled the bulge emission by an ellipsoidal distribution with a Gaussian radial profile in longitude and latitude with FWHM of $\Gamma_l = 8°$ and $\Gamma_b = 7°$. For the disk emission, we adopted the old stellar disk of Robin et al.(2003). The resulting spectra are depicted in Fig. 3. The spectra of the annihilation radiation were modelled by three components: two Gaussians representing narrow and broad 511 keV line emission, and the Ps continuum. The latest bulge spectrum is consistent with the results obtained from the first year data (Jean et al.(2006a)), except for a slight decrease in flux which is due to differences in the model for the saptial distribution of the disk emission. In the Galactic disk spectrum, both the 511 keV line and the Galactic diffuse continuum emission are significantly detected. In addition, there is strong evidence for Ps continuum emission. The 511 keV line is not yet resolved, an upper limit on the line width being 2.2 keV FWHM (90% confidence level). The broad 511 keV line component is not yet significantly detected from the disk. A lower limit on the Ps fraction in the disk emission is about 90% (in the bulge, it is about 97%).

4 Summary and Prospects

The analyses we have performed to date, taking advantage of more than 2 years of observations, clearly demonstrate that SPI detects 511 keV annihilation line emission from outside the central or bulge region of the Galaxy. SPI now detects disk emission at a significance level of about 6σ, allowing us to perform the first spectroscopic study of this emission with SPI. In addition, with SPI we find tantalizing hints at possible halo-like emission. With the existing data, we cannot yet determine whether the emission around the bulge region originates from a halo-like component or from a disk component that is very extended in latitude. In particular, the latitude distribution of the disk cannot be determined independently of assumptions about the distribution of emission in and around the bulge region. It is hoped that INTEGRAL will continue to operate for many years and make further advances possible.

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