PROCEEDINGS OF SCIENCE

Overview of the 511 keV diffuse emission

P. Jean[*]
Centre d'Etude Spatiales des Rayonnements, CNRS/Université de Toulouse
E-mail: `jean@cesr.fr`

The 511 keV gamma-ray line emission from the inner part of our Galaxy is the signature of annihilation of low energy positrons in this region. This emission has been observed and studied since the seventies, and though several sources have been proposed (type Ia supernovae, low mass X-ray binaries, Sgr A*, dark matter...), the origin of Galactic positrons remains an open question. We present the status of our knowledge on this topic in view of recent measurements made with the spectrometer SPI onboard ESA's INTEGRAL observatory. Assuming that positrons do not propagate far from their sources, the morphology of the 511 keV line emission should be tied to the spatial distribution of sources. However, the transport mechanism of positrons in the interstellar medium is still uncertain and recent studies suggest that positrons could propagate more or less far from their source before annihilating, depending on their initial kinetic energy. Implications of measurements and propagation studies on the possible origin of galactic positrons is briefly discussed.

The Extreme sky: Sampling the Universe above 10 keV - extremesky2009,
October 13-17, 2009
Otranto (Lecce) Italy

PoS(extremesky2009)072

---

[*] Speaker.

1. Introduction

The origin of Galactic positrons is a mystery. Although the physical processes producing positrons are quite well known and possible sources are identified (^{56}Co from SNIa, ^{26}Al and ^{44}Ti from massive stars, cosmic-rays…), it is still difficult to explain the amount of positrons annihilating in the Galactic Centre (GC) region. Understanding of the origin of Galactic positrons is one of the major scientific objectives of the INTEGRAL mission. Assuming that positrons do not propagate far from their sources, the spatial distribution of the annihilation emission should trace the spatial distribution of the sources. The spectral analysis of the annihilation emission constitutes an important diagnostic tool for the physical properties of the interstellar medium (ISM) where positrons annihilate (see Guessoum et al. 2005).

In this paper we present an overview of our understanding of the annihilation emission in our Galaxy. In Sec. I, we present the status of the observations of the 511 keV emission before INTEGRAL. In Sec. II, we present the results obtained with INTEGRAL. In Sec. III, we summarize the most recent theoretical investigation on the origin of positrons.

2. Measurements before SPI/INTEGRAL

The 511 keV line emission was first detected from the Galactic center region in the early 1970ies, by balloon borne low energy resolution spectrometers (Johnson et al. 1972, Johnson et al. 1973, Haymes et al. 1975). It was unambiguously identified a few years later with high resolution germanium detectors (Leventhal et al. 1978, Albernhe et al. 1981, Leventhal et al. 1980). Albernhe et al. (1981) recognized that the flux measured by the various balloon-borne experiments increased with increasing size of the detector's field of view, which could mean that the 511 keV line emission was extended along the Galactic plane. The satellite-borne Ge spectrometer HEAO3 confirmed the 511 keV line emission but measured a significant reduction of the flux from the GC region between fall 1979 and spring 1980 (Riegler et al. 1981). This variation has been explained assuming that the emission originates in a single variable compact source at the GC. The variable source hypothesis was reinforced by measurements with balloon-borne Ge or NaI detectors in the 80's and early 90's which showed different results - even significant non-detections of the emission (Leventhal et al. 1982, Paciesas et al. 1982, Leventhal et al. 1986, Niel et al. 1990, Gehrels et al. 1991, Leventhal et al. 1993, Smith et al. 1993). However, reanalysis of the HEAO3 data indicated no variability (Mahoney et al. 1988, Mahoney et al. 1994). Moreover, observations of the GC region in the 1981-1982 and 1984-1985 periods by the seven NaI detectors of SMM provided no evidence for any variability in the intensity of the source, the maximum variation year to year being less than 30% (Share et al. 1988).

Before the launch of CGRO in 1991 with its OSSE collimated spectrometer, the spatial distribution of 511 keV line emission was only poorly constrained. Nine years of OSSE observations, combined with SMM and TGRS data, improved this situation. The first maps presented in Purcell et al. 1997, showed evidence for three distinct features: a central bulge, an emission from the Galactic plane and an enhancement or extension of the emission at positive latitudes above the GC (hereafter PLE). This latter component was difficult to explain. Milne et al. (2000), revisited these data by testing several bulge and disk models and including the orthopositronium continuum emission in their analyses. They show that extended bulge models are favored over a GC point

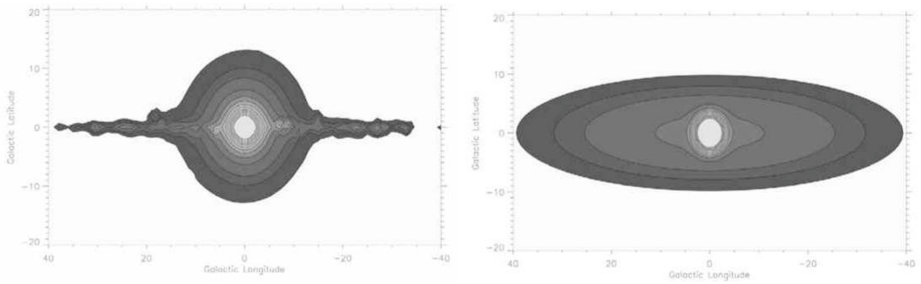

Figure 1: Bulge dominated (left) and disk dominated (right) solutions to explain OSSE, TGRS and SMM data (Milne et al. 2002).

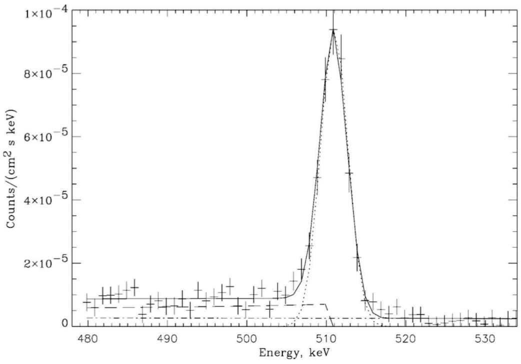

Figure 2: Spectrum extracted from TGRS data assuming a gaussian spatial distribution of FWHM 30^o (Harris et al. 1998).

source and that the flux in each component depends strongly upon the assumption of the bulge shape (see Fig. 1). The ratio of the intensity of the bulge to the disk component (hereafter B/D) ranged from 0.2 to 3.3 (Milne et al. 2000 and 2002). They found a flux in the PLE 8 times lower than the flux presented by Purcell et al. 1997. Moreover, no PLE was visible in the image of the orthopositronium continuum.

Concerning the spectral characteristics of the annihilation emission, several reports on observations with Ge spectrometers provide a width of the line in the 2–3 keV range (Smith et al. 1993, Leventhal et al. 1993, Harris et al. 1998). Using only OSSE data, Kinzer et al. (1996) present a distribution of the continuum positronium. They derived a positronium fraction of 0.97±0.03. Measurements with the Ge detector TGRS gives a compatible value of 0.94±0.04 (Harris et al. 1998). Fig. 2 shows the spectrum of the annihilation emission obtained with TGRS data.

The status of the observations of the annihilation emission before INTEGRAL is as follows: the 511 keV line flux is $\sim$ 2 - 3 $\times$ 10^{-3} cm^{-2} s^{-1} with a large uncertainties on the morphology of the emission. The variations of the 511 keV flux measured by various experiments, were not only due to the difference in their fields of view but also to systematic effects induced by the intense instrumental background at this energy. Indeed, cosmic-ray particles interacting with materials of (and close[1] to) spectrometres produce positrons, resulting in a strong instrumental background at

---

[1] e.g. spacecraft for space-borne spectrometres and gondola and atmosphere for balloon-borne spectrometres.

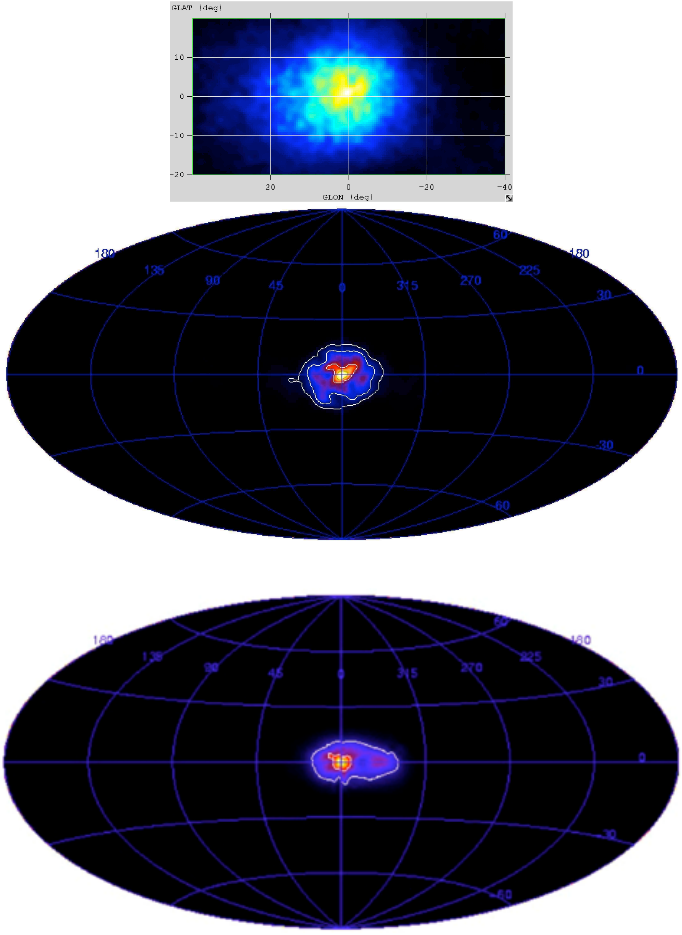

Figure 3: Images of the sky at 511 keV obtained with SPI after (top) 2 months (Knödlseder et al. 2003), (middle) 1 year (Knödlseder et al. 2005) and (bottom) 4.5 years of observation (Weidenspointner et al. 2008).

511 keV (e.g. the signal to noise ratio is ∼1% for SPI – Jean et al. 2003) which illustrates the difficulties of 511 keV line astronomy. The challenge is to identify and to remove such systematics in the data analysis.

3. Observations with SPI/INTEGRAL

SPI has been specifically designed to measure diffuse gamma-ray line emissions, particularly at 511 keV. SPI consists of an array of 19 germanium detectors with an energy resolution of 2 keV at 511 keV, surrounded by an active anticoincidence shield/collimator defining a field of view of $\sim 16^o$ FWHM. A coded aperture mask is associated with the germanium detectors, providing an angular resolution of $\sim 2.5^o$. Detailled description of SPI and its performance can be found in Vedrenne et al. (2003) and Roques et al. (2003), respectively.

The temporal (dithering and pointings) and spatial (coded mask) modulation of the astrophysical signal measured by SPI allows to image the emission. Images, obtained using the Richardson Lucy algorithm (Knödlseder et al. 2007) and Bayesian imaging reconstruction methods (Allain &

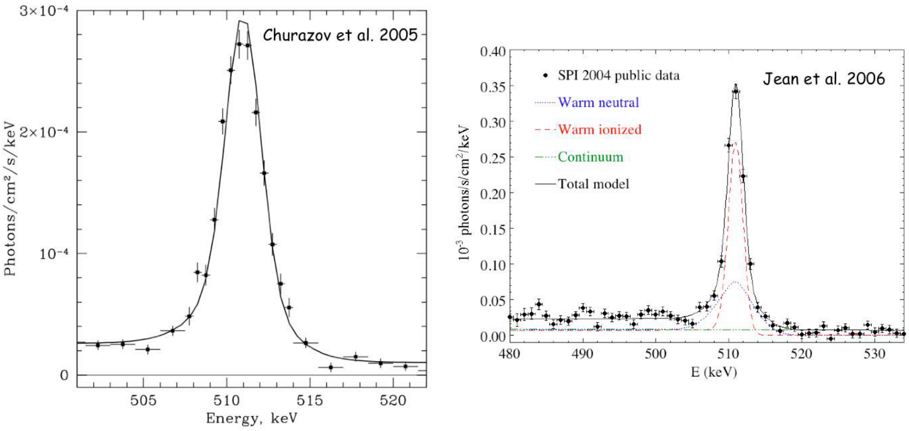

Figure 4: Spectrum extracted from SPI data by (left) Churazov et al. (2005) and (right) Jean et al. (2006).

Roques 2006), show a rather extended emission from the Galactic bulge. Fig. 3 shows the images of the sky at 511 keV obtained after 2 months, 1 year and 4.5 years of mission. The first image of the annihilation line suggested a spherically symmetric Galactic bulge component. Analysis of the spatial distribution by model fitting methods lead to a FWHM of $\sim 8^{o}$ (Jean et al. 2003). This particular morphology triggered the interest of physicists researching signatures of dark-matter particles (e.g. Boehm et al. 2004). After 1 year of observation, the exposure in the Galactic plane was sufficient to detect the disk emission providing a bulge to disk flux ratio ranging from 1 to 3 and a total 511 keV line flux of $\sim 2 \times 10^{-3}$ cm^{-2} s^{-1} (Knödlseder et al. 2005), in agreement with OSSE data. Analysis of these data shows that there is no evidence for a point like source in addition to the diffuse emission and there is no evidence for a PLE emission as reported from OSSE measurements (see previous section). The derived flux in the disk can be explained by β^{+} decay of ^{26}Al and ^{44}Ti released by massive stars. The image obtained after 4.5 years showed an asymmetry of the emission from the inner Galactic disk. The 511 keV flux at negative longitudes being $1.8\ ^{+0.5}_{-0.3}$ times larger than at positive longitudes. A similar asymmetry is observed in the distribution of low-mass X-ray binaries emitting at high energies, suggesting that they might be a dominant source of positrons. This asymmetry is still matter of debate and recent analyses presented by Bouchet et al. (2009) and Churazov et al. (2009) find no evidence for a disk asymmetry. Finally, no point sources has been detected at 511 keV in the analysis of IBIS data (De Cesare et al. 2009).

Results of the spectral analysis of the bulge emission based on the first year of measurement with SPI, were presented by Churazov et al. (2005) and Jean et al. (2006). Though the data analysis methods and the approaches were different, both studies lead to the same conclusions. The spectral distribution of the annihilation emission can be explained by the sum of a narrow and a broad unshifted 511 keV lines plus an orthopositronium continuum. The fraction of positrons annihilating via positronium derived from SPI data are 0.94±0.06 (Churazov et al. 2005) and 0.97±0.02 (Jean et al. 2006), in agreement with OSSE and TGRS data. Fitting the measured spectral distribution with spectral models based on the physics of the annihilation of positrons in the ISM yields to the following conclusions. The observed spectrum (see Fig. 4) can be explained by positrons annihilating either in a single phase with a temperature ranging from 7000 to 40000 K and an ionized fraction >1%, either in the warm ionized and neutral medium of the interstellar medium. However, we cannot exclude that a fraction (e.g. $< 20\%$) of the positrons annihilate in the cold phase. Finally, there were not enough statistics to derive physical conditions of the interstellar medium where positron annihilate in the disk (Weidenspointner et al. 2008).

4. Discussions on the origin of positrons

Assuming that positrons do not propagate far from their sources, the observed spatial distribution (large B/D) of the annihilation emission suggest that sources belong to the old population such as SNIa and LMXB. These sources are good candidates since they produce positrons in the decay of ^{56}Co in SNIa and by the pair creation process in the central region of the accretion disk in LMXBs. The main difficulty is to explain how positrons escape the dense region where they are produced. Recent analysis of bolometric observations of the late light curves of some SNIa suggested that no positrons escape (e.g. Leloudas et al. 2009). Positrons produced in the inner part of the accretion disk of LMXB could be ejected through winds or jets (see Guessoum et al. 2006 and reference therein), but the fraction of escaping positrons and the nature of the jets are not well known. Independently of the escaping fraction, the yield of positrons produced by SNIa and LMXB could explain the annihilation rate in our Galaxy, but the observed large B/D ratio of the annihilation emission is difficult to explain with these sources, assuming that positrons do not annihilate far from their sources.

On the other hand, the flux of the 1.8 MeV line emission (resulting from the decay of ^{26}Al nuclei) in the disk yields to a rate of positrons that can explain the rate deduced from the measurement of 511 keV flux in this region. Moreover, recent analysis of the spatial distribution of the 1.8 MeV line shows an asymmetry which is similar to the one of the 511 keV line; the 1.8 MeV line flux at negative longitudes being 1.3 ± 0.2 times larger that at positive longitudes. ^{26}Al (and ^{44}Ti) nuclei produced by massive stars are therefore very good candidate to explain the Galactic disk emission.

The origin of positrons annihilating in the bulge is more complicated. First, the bright spherically symmetric diffuse annihilation emission from the bulge suggested that positrons could be produced in annihilation of light dark matter particles (Boehm et al. 2004). This particle should have a mass of 1-100 MeV, i.e. lower than standard dark matter particle candidates (e.g. neutralino). Such a property avoid the channel of their annihilation with a production of high energy photons that have not been indeed observed. The lack of high energy emission from the bulge put an other constraint on the mass of the light dark matter particles. Indeed, if dark matter particles had a mass larger than ~ 10 MeV they would have produced relativistic positrons which should have produced unseen high-energy photons in their direct annihilation in flight with electrons of the ISM, as proposed by Beacom & Yüksel (2006) and Sizun et al. (2006). However, these authors did not take into account the energy loss of positrons by synchrotron which could increases further the upper limit of their initial kinetic energy depending on the magnetic field intensity which is not yet clearly determined in the GC regions (Chernishov et al. 2009). Cheng et al. (2006, 2007) and Totani (2006) proposed that positrons annihilating now in the bulge, originate from Sgr A * activity in the past. First authors proposed that positrons were produced by the disruption of stars accreted by the super massive black-hole 10^4-10^5 years ago. The second author proposed that steady state production of positrons during the accretion of surrounding gas on Sgr * was 10^4 higher in the past. It would have been interrupted by the expansion of the SNR Sgr East.

Discussions on the origin of positrons are often based on the assumption that the spatial distribution of the annihilation emission reflects the spatial distribution of the sources. This is true if the positrons do not propagate far from their sources. In order to explain the large B/D ratio, Prantzos (2006) and Hidgon et al. (2009) suggested that positrons from SNIa in the disk may travel a large distance and then annihilate in the bulge. Jean et al. (2009) reviewed the different processes that affect the transport of positrons in the ISM. They distinguished 3 kinds of transport: diffusion via scattering off MHD waves, ballistic motion perturbed by collisions with particles of the ISM (also called "collisional regime"), and advection with large-scale fluid motions. They found that positrons do not scatter off MHD waves in neutral media. Positrons scatter off MHD waves in ionized media when their kinetic energy is higher than a threshold which depends on the physical parameters of the local ISM, but uncertainties in MHD waves properties in this medium cast some doubt on this conclusion. Positrons that do not scatter off MHD waves propagate in the collisional regime. In this case, they can travel very large distance (up to $\sim$10 kpc for 1 MeV positron in a density of 1 cm^{-3}) along magnetic field lines before they annihilate.

5. Conclusions

Images and spectroscopy of the annihilation emission tell us that positrons annihilate mainly in the warm media of the Galactic bulge. The annihilation emission in the disk is weak and possibly asymmetric. Clarifying the asymmetric or symmetric nature of the spatial distribution of the annihilation emission is one of the major aim of present and future observations with SPI.

Measurements of SPI initiated a significant number of theoretical investigations on the origin of positrons. But effort should be made to understand the propagation of positrons in our Galaxy. Several studies suggest that positrons may travel a large distance before they annihilate in the ISM but uncertainties remain on the propagation mode, particularly in the ionized phases. Understanding the transport of positrons in the ISM is the missing link which would make the connection between the spatial distribution of sources and the (observed) spatial distribution of the annihilation emission.

References

[1] Albernhe, F. et al., 1981, A&A, 94, 214

[2] Allain, M. & Roques, J.P., 2006, A&A, 447, 1175

[3] Beacom, J.F. & Yuksel, H., 2006, Phys. Rev. Lett., 97, 1102

[4] Boehm, C. et al., 2004, Phys. Rev. Lett., 92, 101301

[5] Bouchet, L. et al., 2009, this proceedings

[6] Cheng, K.S. et al., 2006, ApJ, 645, 1138

[7] Cheng, K.S. et al., 2007, A&A, 473, 351

[8] Chernyshov, D.O. et al., 2009, MNRAS, in press

[9] Churazov, E. et al., 2005, MNRAS, 1377, 1386

[10] Churazov, E. et al., 2009, this proceedings

[11] De Cesare, G. et al., 2009, this proceedings

[12] Guessoum, N., Jean, P. & Gillard, W., 2006, A&A, 436, 171

[13] Guessoum, N., Jean, P. & Prantzos, N., 2006, A&A, 457, 753

[14] Harris, M.J. et al. 1998, ApJ, 501, L55

[15] Haymes, R.C. et al., 1975, ApJ, 201, 593

[16] Higdon, J.C. et al., 2009, ApJ, 698, 350

[17] Jean, P. et al., 2003, A&A, 407, L55

[18] Jean, P., et al., 2006, A&A, 445, 579

[19] Jean, P., et al., 2009, A&A, 508, 1099

[20] Johnson, W.N., Harnden, F.R., and Haymes, R.C. 1972, ApJ, 172, L1

[21] Johnson, W.N., & Haymes, R.C. 1973, ApJ, 184, 103

[22] Kinzer, R.L., et al., 1996, A&ASS, 120, 317

[23] Knödlseder, J. et al., 2003, A&A, 411, 457

[24] Knödlseder, J. et al., 2003, A&A, 441, 513

[25] Knödlseder, J. et al., 2007, ESA Special Publication, vol. 622, 13

[26] Leloudas, G. et al., 2009, A&A, 505, 265

[27] Leventhal, M., MacCallum, C.J., & Stang, P.D. 1978, ApJ, 225, L11

[28] Leventhal, M., et al., 1980, ApJ, 240, 338

[29] Leventhal, M., Huters, A.F. & Stang, P.D. 1982, ApJ, 260, L1

[30] Leventhal, M., et al., 1986, ApJ, 302, 459

[31] Leventhal, M., et al., 1993, ApJ, 405, L25

[32] Mahoney, W.A., et al., 1988, AIPC, 170, 149

[33] Mahoney, W.A., et al., 1994, ApJSS, 92, 387

[34] Milne, P.A. et al., 2000, AIPC, 510, 21

[35] Milne, P.A. et al., 2002, New Astr. Rev., 46, 553

[36] Niel, M. et al., 1990, ApJ, 356, L21

[37] Paciesas, W.S., et al., 1982, ApJ, 260, L7

[38] Prantzos, N., 2006, A&A, 449, 869

[39] Purcell, W.R., et al., 1997, ApJ, 491, 725

[40] Riegler, G.R., et al., 1981, ApJ, 248, L13

[41] Roques, J.P., et al., 2003, A&A, 411, L91

[42] Share, G.H. et al., 1988, ApJ, 326, 717

[43] Sizun, P., Cassé, M. & Schanne, S., 2006, Phys. Rev. D, 74, 063514

[44] Smith, D.M., et al., 1993, ApJ, 414, 165

[45] Totani, T., 2006, Publ. Astron. Soc. Japan, 58, 965

[46] Vedrenne, G., et al., 2003, A&A, 411, L63

[47] Weidenspointner, G., et al., 2008, Nature, 451, 159