

POSITRON ANNIHILATION IN THE MILKY WAY

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Abstract. I review our current understanding of positron sources in the Galaxy, on the basis of the reported properties of the observed 511 keV annihilation line. It is argued here that most of the disk positrons propagate away from the disk (due to the low density environment) and the resulting low surface brightness annihilation emission is currently undetectable by SPI/INTEGRAL. It is also argued that a large fraction of the disk positrons may be transported via the regular magnetic field of the Galaxy into the bulge and annihilate there. These ideas may alleviate current difficulties in interpreting INTEGRAL results.

1 Introduction

The origin of the Galactic electron-positron annihilation radiation remains problematic ever since the original detection of its characteristic 511 keV line (e. g. Diehl et al. 2006 and references therein). Recent observations of the line intensity and spatial morphology with the SPI instrument aboard INTEGRAL put severe constraints on its origin, since it appears that $1.5 \pm 0.1 \cdot 10^{43} \text{ e}^+/\text{s}$ are annihilated in the bulge alone and $0.3 \pm 0.2 \cdot 10^{43} \text{ e}^+/\text{s}$ in the disk, i.e. that the bulge/disk ratio of annihilating positrons is $B/D \sim 3-9$ (Knödlseeder et al. 2005).

Weidenspointer et al. (2008) find a significant asymmetry in the disk emission (factor 1.7 between positive and negative latitudes). They also find that the observed distribution of low-mass X-ray binaries in the hard state has a remarkable similarity to the 511 keV longitude profile; they suggest then that those objects may be the main sources of positrons in the disk, with a sizeable (but insufficient) contribution to the bulge emission.

In this short review, I discuss the Galactic positron sources in the light of recent developments. I argue that, *if it is assumed that positrons annihilate near their sources*, then none of the proposed positron production sites, either conventional or “exotic” ones, completely satisfies the observational constraints. Furthermore, I argue that a large fraction of the disk positrons, produced by thermonuclear supernovae (SNIa) or other sources, may be transported via the regular magnetic field of the Galaxy into the bulge, where they annihilate. This increases both the bulge positron annihilation rate and the bulge/disk ratio, alleviating considerably the constraints imposed by the SPI/INTEGRAL data analysis. In fact, I argue that the SPI data are compatible with values of B/D as low as 0.5, because positrons can propagate away from their sources and fill a rather large volume (of low surface brightness), much larger than the relatively thin disks adopted in the analysis of SPI data. This property is crucial to the success of the scenario proposed here, which depends also on the poorly known properties of the Galactic magnetic field. In any case, the issue of positron propagation in the ISM and the magnetic field of the Galaxy appears to be crucial for our understanding of the 511 keV emission.

2 Positron sources in the Galaxy

Thermonuclear supernovae (SNIa) are prolific e^+ producers, releasing on average $3 \cdot 10^{54}$ positrons (from the decay of $\sim 0.7 M_{\odot}$ of ^{56}Co), but most of them annihilate inside the SN. Assuming that N_{e^+} positrons escape each SNIa and that the rate of SNIa in the Galactic bulge and disk *per unit stellar mass* is R_{Ia} (given by observations of SNIa in external galaxies), one finds that the e^+ production rate from ^{56}Co radioactivity of SNIa is $L = M R_{\text{Ia}} N_{\text{e}^+}$, where M is the stellar mass of the system. N_{e^+} is currently the major uncertainty of the problem. Original estimates, based on late optical lightcurves of SNIa, gave $N_{\text{e}^+} \sim 8 \cdot 10^{52}$ or an escaping

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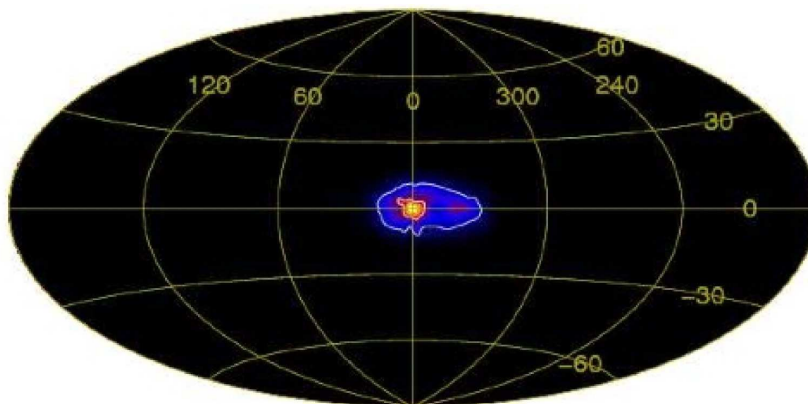


Fig. 1. Image of the Galactic 511 keV emission, after 5 years of SPI/INTEGRAL data (Weidenspointner et al. 2008). A strong bulge emission and a weak asymmetric disk are seen.

fraction $f \sim 0.03$ (Milne et al. 1999).¹ Taking into account the masses of the MW disk and bulge, as well as the corresponding SNIa rates, this number leads to a positron emissivity $L_D = 1.95^{+0.98}_{-0.93} 10^{43} e^+/s$ for the disk and $L_B = 0.17^{+0.083}_{-0.081} 10^{43} e^+/s$ for the bulge (see e.g. Prantzos 2006). Those estimates suggest that the disk e^+ emissivity is slightly larger than the total galactic e^+ annihilation rate required by SPI observations, but it is much larger than the one of the bulge, contrary to observations.

In the case of the disk positrons, a major source is undisputably the radioactivity of ^{26}Al . The observed decay of the $\sim 2 M_\odot$ of ^{26}Al per Myr (see Diehl, this volume) provides about $0.4 10^{43} e^+/s$, i.e. close to the value given by the latest SPI data for the disk positron annihilation rate. However, the 1.8 MeV map of ^{26}Al does not show the degree of asymmetry claimed in Weidenspointner et al. (2008) for the disk 511 keV emission.

Among the other astrophysical sources of positrons, X-ray binaries (XRBs) or some related class of objects, appear as plausible candidates. Low-mass XRBs (LMXRBs) were suggested in Prantzos (2004), who noticed that their observed longitude distribution in the Galaxy is strongly peaked towards the central regions, not unlike the one of the 511 keV emission. He also noticed, however, that most of the strongest sources (counting for 80% of the total Galactic X-ray flux) are evenly distributed in the Galactic plane, with no preference for the bulge; if their positron emissivity scales with (some power of) their X-ray flux, then LMXRBs cannot be at the origin of the bulge Galactic positrons.

According to Weidenspointner et al. (2008), the observed asymmetry in the disk 511 keV emission² matches closely the Galactic distribution of LMXRBs in their hard state (factor 1.7 in both cases between positive and negative Galactic longitudes) and this similarity suggests that disk positrons mostly originate from this particular class of compact objects. It should be noted, however, that in all probability, at least half of the disk 511 keV emissivity is due to ^{26}Al , which displays only a small degree of asymmetry. The remaining 511 keV emission (i.e. once the ^{26}Al contribution is removed) is certainly even more asymmetric (factor >2.5) and no known source matches such an asymmetric profile; thus, it seems premature to conclude that hard-state LMXRBs are at the origin of Galactic positrons.

Guessoum et al. (2006) find that another sub-class of XRBs, micro-quasars, are interesting positron producers. Although it is not known whether their jets contain mostly positrons or protons, theoretical estimates evaluate their individual positron emissivity up to $\sim 10^{41} e^+/s$. Coupled with their estimated number in the Milky Way (of the order of 100), that value suggests that micro-quasars may be interesting candidates.

If the Galactic SNIa positron emissivity evaluated in the first paragraph of this section is close to the real one, but the source of the observed bulge emission turns out to be different, it should then be a rather strange

¹Observations of the late *bolometric* lightcurves of two SNIa (Sollerman et al. 2004; Strinziger and Sollerman 2007) are compatible with zero escaping fraction (or $N_{e^+}=0$) in the framework of 1-D models for SNIa. In "canonical" 1-D models, ^{56}Co is produced and remains in the inner part of the SNIa. However, hydrodynamical 3-D models and recent observations (Tanaka et al. 2008) suggest that a sizeable fraction of ^{56}Co may be found in the outermost, highest velocity layers, from which positrons may, perhaps, escape. In any case, the (presently unknown) configuration of the SNIa magnetic field is crucial for the issue of e^+ escape.

²Note that this finding is not confirmed in a recent analysis by Bouchet et al. 2008.

coincidence. We argue here that transport of disk positrons to the bulge through the Galactic magnetic field may inverse the Disk/Bulge ratio of e^+ annihilation rates. The arguments are valid for any other source producing positrons of ~ 1 MeV, such as those resulting from radioactivity or X-ray binaries, or microquasar jets.

3 Positron propagation in the Galaxy

Positrons released in the ISM (especially in its less dense regions, like e.g. outside spiral arms or outside the thin gaseous layer) propagate affected by the Galactic magnetic field. The large scale regular magnetic field (MF) of the Milky Way is composed of a toroidal (disk) component (probably bisymmetric) and a poloidal (halo) component, probably in the form of a A0 dipole (see Han 2004 and references therein also Fig. 1). At Galactocentric distance $r=8$ kpc the toroidal component has a strength of a few μG (Beck et al. 1996) and dominates the poloidal one (a few tenths of μG). However, the former varies as $1/r$, while the latter as $1/r^3$ and should therefore dominate in the inner Galaxy.

Positron propagation is strongly affected by the irregular (turbulent) component of the galactic MF, which is comparable in intensity with the regular one near the local disk. Unfortunately, the properties of the irregular component away from the disk plane are even less well understood than those of the regular components (e.g. Han 2004). Prouza & Smida (2003) assume that the turbulent component occupies 80% of the volume inside spiral arms, 20% of the volume outside spiral arms and within vertical distance $|z| < 1.5$ kpc and only 1% of the volume at larger distances. On the other hand, cosmic ray propagation models indicate that the size of the cosmic ray “halo” (CRH, i.e. the region inside which cosmic rays diffuse on inhomogeneities of the magnetic field) is $z_{CRH} > 3$ kpc, based on measurements of unstable/stable ratios of secondary nuclei (Strong & Moskalenko 2001). If e^+ escape from the CRH then positron propagation at large distances from the disk will be dominated by the regular MF, i.e. the poloidal field. In those conditions, a fraction of the positrons produced from disk SNIa will ultimately find their way into the bulge.

Taking into account the SPI data (see Sec. 1) and the SNIa emissivity of positrons in the disk and the bulge (Sec. 2) it turns out that in order to explain the observed bulge annihilation rate by SNIa, the fraction of disk positrons channeled to the bulge must be $f_{ESC} \sim 0.5$, (i.e. $\sim 10^{43}$ e^+ /s from the disk have to join the $0.17 \cdot 10^{43}$ e^+ /s produced in the bulge and annihilate in that region.

This fraction may not be unreasonable. For instance, reacceleration of e^+ by shock waves of SNIa may considerably increase the thermalization (travel) time of positrons τ_{SD} . On the other hand, the positron confinement time in the disk may be shorter than the standard value of $\tau_{CONF} \sim 10^7$ yr. The reason is that, because of their low energy (and correspondingly low gyroradius in the Galactic MF) 1 MeV positrons may diffuse very little on the density fluctuations of the MF, and thus they may escape more easily than the higher energy particles of standard Galactic cosmic rays. These arguments are discussed further in Prantzos (2006), while Jean et al. (2006) find that low energy positrons may travel distances of several kpc in the hot, tenuous interstellar medium (which dominates away from the disk of the Milky Way).

In Prantzos (2006) it is also argued that the SNIa disk positrons may not only leave the disk, but also enter the bulge by avoiding the “magnetic mirror” effect. The reason is that their velocity has a dominant component which is always parallel to the lines of the regular magnetic field of the Galaxy. When positrons are still in the cosmic ray halo, they diffuse on the turbulent component of the MF at small scales, but at large scales their diffusive motion follows the regular (toroidal) component. The configuration of the Galactic MF can vary only smoothly between the regions where the various components of the regular field (toroidal in the disk and poloidal away from it) dominate. The toroidal field changes smoothly into a poloidal one and positrons leaving the former enter the latter with a velocity essentially parallel to its field lines; this minimizes the losses due to the mirror effect.

It is then concluded that 1) MeV positrons produced in the disk may propagate away from it, and 2) they may also be channelled to the bulge and annihilate there. In Fig. 2 we calculate the Galactic gamma-ray profile from positron annihilation, as seen with three different levels of sensitivity (appearing in the bottom of each panel). We assume that the Milky Way e^+ annihilation rate results from i) a bulge with annihilation rate $L=1.2 \cdot 10^{43}$ e^+ /s (resulting from transfer of $\sim 50\%$ of the disk SNIa positrons plus those produced by the bulge SNIa population), ii) a “thick disk” (scaleheight 3 kpc) from the remaining SNIa positrons, and iii) a thin disk (from positrons released by ^{26}Al decay and annihilating in the thin gaseous layer). Of course, such a symmetric model does not reproduce the small disk asymmetry reported in Weidenspointer et al. (2008).

We show quantitatively (and with more details in Prantzos 2006) that the SPI/INTEGRAL data are fully

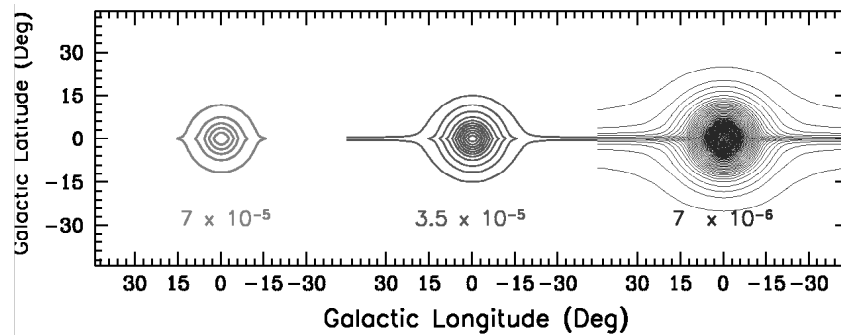


Fig. 2. Simulated profile of the 511 keV emission of the Milky Way in galactic coordinates, as seen at three different levels of detector sensitivity (indicated in the bottom of each panel, in $\text{ph}/\text{cm}^2/\text{s}$). The adopted composite model for the positron annihilation (bulge + thin disk + thick disk) is described in Sec. 3.

compatible even with bulge/disk ratio of e^+ annihilation rates lower than 1, provided that sufficiently (but not unreasonably) extended positron distributions are considered. The model proposed here exploits a range of possibilities, given our poor understanding of the Galactic magnetic field and of the propagation of low energy positrons in it. Its assumptions may be tested, through future observational and theoretical developments. Multi-wavelength studies of SNIa, including the infrared, will determine ultimately the typical positron yield of those objects. A small 511 keV emission outside the bulge is currently seen by SPI/INTEGRAL and, given enough exposure, the spatial extent of that emission will be determined (by INTEGRAL or a future instrument); an extended disk emission will prove that positrons travel indeed far away from their sources. The morphology of the Galactic magnetic field, and especially the presence of a poloidal component, will be put on more sound basis through further measurements (e.g. Han 2004).

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