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Positron Propagation and the INTEGRAL/SPI 511 keV Bulge/Disk Ratio

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The Galactic bulge/disk ratio of 511 keV positron annihilation radiation measured by INTEGRAL/SPI and the bulge/disk ratio of Galactic supernovae differ significantly. We show, however, that this difference can be understood in the context of a Galactic supernova origin of positrons from decay of nucleosynthetic ^{56}Ni, ^{44}Ti, and ^{26}Al, if the detailed propagation of these MeV positrons in the various phases of the interstellar medium is also taken into consideration. These relativistic positrons must first slow down to energies <10 eV before they can annihilate, and therefore can travel significant distances before annihilating. We show that about 72% of the positrons resulting from supernovae nucleosynthesis are born in the hot (10^6K) tenuous phase of the interstellar medium, because of its large filling factor. However, they do not annihilate there because they stream out of this medium and either escape into the overlying halo, or slow down and annihilate in the much denser, warm (10^4K) ionized and neutral phases — predominately the outer envelopes of molecular clouds. This propagation explains the observed shape of the 511 keV positron annihilation line and the ratio of the line to positronium continuum fluxes. Such propagation also explains the observed bulge/disk ratio of the annihilation radiation, since more than half of the positrons born in the disk escape into the bulge and halo. Further, we predict that the bulk of the broad (5.4 keV) component of the 511 keV line emission comes from the 0.5–1.5 kpc region of the bulge, while much of the narrow (1.3 keV) component of the line emission originates in the central 0.5 kpc. Note: Although a larger paper, on which this is based, has been revised and updated for the *Astrophysical Journal*, using more recent INTEGRAL measurements, this paper gives only what was presented at the meeting, and the conclusions are still the same.

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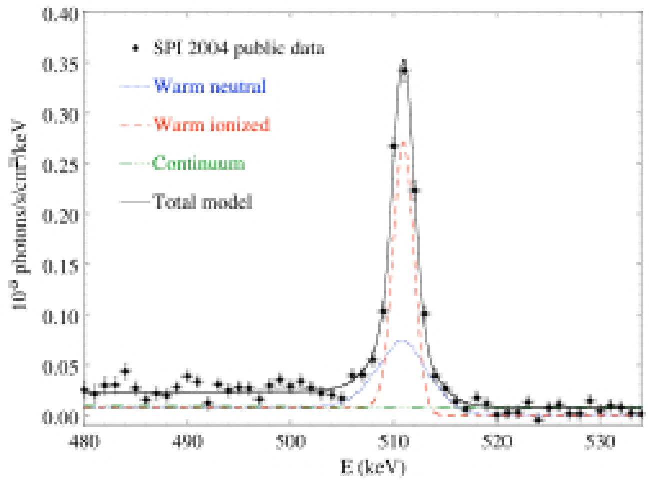

Figure 1: INTEGRAL/SPI spectrum of the 511 keV positronium annihilation line and 3-γ continuum from Jean et al. 2006, with the modeled components.

1. Introduction

The discovery (Johnson, Harnden & Haymes 1972; Leventhal et al. 1979) of the diffuse Galactic positron annihilation radiation at 511 keV from the inner Galaxy has led to extensive studies of the possible origin of the annihilating positrons.These studies have shown (e.g., Ramaty & Lingenfelter 1979; Knödlseder et al. 2005) that, of all the various potential sources, positrons from the decay of radioactive nuclei produced by explosive nucleosynthesis in supernovae are the most intense, and, hence, most likely source. Analyses of the measurements by the SPI gamma-ray spectrometer on INTEGRAL of the 511 keV line (Fig. 1) and all-sky distribution of the Galactic positron annihilation radiation have shown that the bulge-to-disk luminosity ratio is ~3.0±1.0 (Knödlseder et al 2005), and more recently, ~1.7±0.4 (Weidenspointner et al. 2007).

2. The “Bulge to Disk Ratio Problem”

Assuming simply that the positron annihilation and production rates are in local equilibrium, these observations have been taken to imply a similar bulge/disk ratio for Galactic positron production. This suggested ratio has seriously challenged previous stellar source models, since it is roughly 3 times larger than that of the time-averaged mean bulge/disk ratio of Galactic supernovae (e.g., Knödlseder et al 2005). Three solutions were suggested: 1) a new, unrecognized, significant source of positrons in the bulge, 2) the spatial/temporal distribution of Galactic supernovae is quite different than previously assumed, or 3) the positron propagation and annihilation environments are very different in the bulge and disk, leading to a significant escape of positrons from the disk into the halo.

2.1 New Source of Positrons? – No!

A new significant source of positrons seems quite unlikely since various recent reviews (e.g., Dermer & Murphy 2001; Knödlseder et al. 2005; Guessoum, Jean, & Prantzos 2006) of the potential Galactic positron sources all conclude that supernovae are still the most plausible source, and that other suggested sources, including cosmic-ray interactions, novae, and various exotic processes, all appear to yield much weaker fluxes or are highly uncertain.

2.2 Different Distribution of Supernovae? – No!

We have re-examined (Higdon, Lingenfelter, & Rothschild 2007) both the positron production by various types of supernovae and the expected bulge/disk ratio of such supernova sources of positrons, in the light of recent observations that suggest there have been temporal variations in the Galactic star formation rate in both the inner disk and bulge. We find that the current observations and models of these variations still do not give a supernova bulge/disk ratio that is at all close to that of the observed annihilation radiation.

2.3 Positron Propagation in the ISM? – Yes!

Lastly, we examined (Higdon, Lingenfelter, & Rothschild 2007) in detail the propagation and annihilation of the β^{+}-decay positrons in the very different environments of the bulge, disk, and halo. Investigating both the physics of MeV electron propagation and the observational evidence of it from extensive measurements of Solar flare and Jovian electrons in the heliosphere, we show that propagation can explain all the observations.

3. Propagation Model and Calculation

We first revisited the production of positrons by β^{+} decay of ^{56}Ni, ^{44}Ti, and ^{26}Al from explosive nucleosynthesis in different types of Galactic supernovae. We also re-examined the rates of such supernovae in the Galaxy and the resulting spatial and temporal distribution of their production of positrons in both the Galactic bulge and disk in the light of recent observations and theory, in order to determine the expected bulge/disk ratio of such positron production. We find that this bulge/disk ratio is not consistent with that of the observed 511 keV radiation.

We modeled the Galaxy in 5 separate regions, shown in Fig. 2, and considered positron production and propagation in the various phases of the ISM within each region, namely the hot, tenuous phase, the warm ionized and neutral phases, and the cold molecular cloud cores (Fig. 3).

The total predicted Galactic positron production from these three isotope chains is (75 f_{56} ν_{Ia} + 1.2 ν_{Ia} + 0.3)$\times 10^{43}$ e^{+}/s, where f_{56} is the fraction of positrons from the ^{56}Ni chain that escape the supernova ejecta, and ν_{Ia} is the rate of Type Ia supernovae per 100 years. We calculate the Galactic supernova rate to be 2.30±0.70 SNu, or about one per 45 years. Of this, ν_{Ia}=0.35±0.14 for SNIa. In order to match the total Galactic positron production rate of (2.0±0.4)$\times 10^{43}$ γ/s (Knodlseder et al. 2005; Weidenspointner et al. 2007), f_{56} must be 5%±2%. This value is quite consistent with calculations by Chan & Lingenfelter ((1993) and with that inferred from SNIa light curves at late times (Milne, The, & Leising 1999). The expected escape fractions of positrons from the much more massive SNII and SNIb/c are negligible, except for ^{26}Al and ^{44}Ti.

We then examined in detail the propagation and annihilation of these positrons in the very different environments of the bulge, disk, and halo where the positrons, born with mean energies of ~0.5 MeV, must first slow down to energies ≤10 eV before they can annihilate (Guessom, Ramaty, & Lingenfelter 1991; Guessom, Jean, & Gillard 2005).

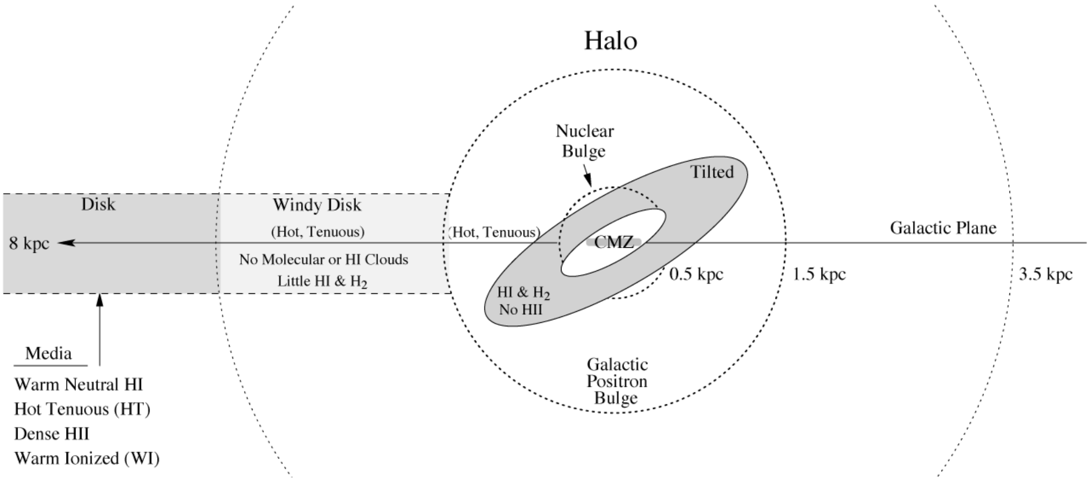

Figure 2: Schematic model of the Galaxy identifying the Central Molecular Zone (CMZ) within the nuclear Bulge (<0.5 kpc), the Tilted Disk within the Positron Bulge (<1.5 kpc), the Windy Disk, and the Disk beyond 3.5 kpc. Temperatures and densities are indicated.

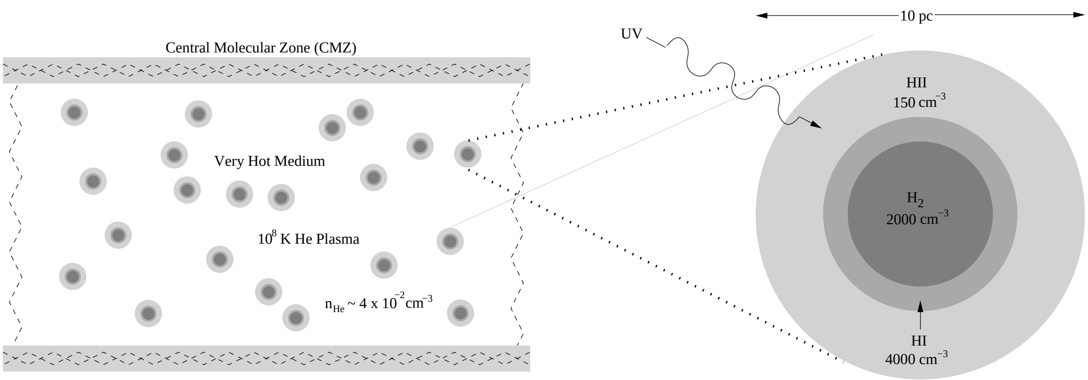

Figure 3: Schematic model of the Central Molecular Zone showing the very hot tenuous medium and the ionizes the outer envelopes of molecular clouds. The concentric structure of the media within a given cloud is also shown. Temperatures and densities are indicated.

We determined the positron mean free path along the local magnetic field in each phase of the ISM from current propagation models based on extensive observations and analyses of Solar flare and Jovian electrons in the interplanetary medium. These models and observations show that propagation perpendicular to the direction of the local field is negligible. Within the positron bulge (<1.5 kpc) the observations suggest that the bulk magnetic field is essentially perpendicular to the Galactic plane, or perhaps dipolar.

SNIa in the nuclear bulge (<0.5 kpc) occur almost entirely in the very hot medium exterior to the molecular clouds of the CMZ. From the propagation calculations, we expect nearly 100% of positrons from these supernovae will encounter the photoionized HII outer shells of the clouds and annihilate there. Essentially none of these positrons will escape beyond the postron bulge (>1.5 kpc).

Observations suggest that only SNIa and SNIp occur in the shell between 0.5 and 1.5 kpc with

Table 1: Results of Modeling the Propagation

511 keV Flux from the Bulge, Disk, and Halo ($\times$10^{-3} photons/cm^2 s)		
	Calculation	**INTEGRAL/SPI**
Bulge(<0.5 kpc)	0.51±0.25	0.38±0.03
Bulge(0.5–1.5 kpc)	0.29±0.14	0.41±0.06
Disk(1.5–8 kpc)	1.64±0.82	1.41±0.35
Halo(1.5–8 kpc)	1.27±0.63	0.86±0.59
Annihilation Rate for the Bulge, Disk, and Halo ($\times$10^{43} e$^+$/s)		
Bulge(<1.5 kpc)	0.97±0.48	1.0±0.25
Disk(1.5–8 kpc)	0.65±0.32	0.6±0.2
Halo(1.5–8 kpc)	0.55±0.27	0.4±0.3
Bulge/Disk	**1.5±0.7**	**1.7±0.4**
Positronium Fraction in the Bulge, Disk, and Halo		
Bulge(<1.5 kpc)	0.92±0.02	0.93±0.09
Disk (1.5–8 kpc)	0.91±0.02	???
Halo (1.5–8 kpc)	0.65±0.07	???
Ratio of Broad to Narrow Line Widthe in the Bulge and Disk		
Bulge (<1.5 kpc)	0.56±0.28	0.48±0.18
Bulge (<0.5 kpc)	0.07±0.04	???
Bulge (0.5–1.5 kpc)	4.9±0.25	???
Disk (1.5–8 kpc)	0.05±0.02	???

no contribution from massive star collapse. Almost all the positrons in this shell are also born in the hot medium, and from the calculated propagation we expect they will encounter clouds and annihilate in the HI shells, since no significant photoionized HII gas is expected, due to the absense of massive stars, and none is observed.

We expect very little (<1%) of the positrons born in the Windy Disk (1.5 – 3 kpc) to annihilate there, because only a negligible amount of warm and cold gas has been observed there. The calculations indicate that nearly all escape along essentially radial magnetic field lines in roughly equal numbers, inwards into the Tilted Disk and outwards to the Halo or Disk beyond 3 kpc. Thus, the annihilation will take place far from the birth sites.

In the Disk beyond 3 kpc, the combined filling factors and concentration of OB associations suggest that roughly half of the positrons will be born in the hot phase of superbubbles, which blow out the magnetic field lines, along which they escape in roughly equal numbers up into the halo and down into the warm ionized phases where they annihilate. The other half are born in the warm phases with about half in the extended neutral gas from which ~80% stream along spiral field lines escaping into the ionized phases and superbubbles.

The results of all of these calculations of the production, propagation, and annihilation of positrons in the various phases of the ISM within the different regions of the Galaxy are summarized in Table 1 together with estimated uncertainties. There we show that such propagation can explain in detail the fluxes of the 511 keV line measured by INTEGRAL/SPI in each region, together with the measured bulge/disk ratio (Knodlseder et al. 2005; Weidenspointner et al. 2007), as well as the measured positronium formation fraction (Churazov et al. 2005;Weidenspointner et al. 2006), and the ratio of broad to narrow 511 keV line emission (Churazov et al. 2005; Jean et al. 2006). Moreover, we predict that the bulk of the broad (5.4 keV) line emission comes from the 0.5–1.5 kpc region of the bulge, while much of the narrow (1.3 keV) line emission originates in the central 0.5 kpc.

4. Summary and Conclusions

In conclusion, we find that roughly half of the Galactic positrons from supernova-generated radionuclei are produced within the stellar bulge of $R < 3$ kpc, and half in the stellar disk beyond that. Essentially all of the bulge positrons are produced in the very hot plasma, through which they diffuse with a calculated mean free path of only 1% of the size of the region. Therefore, before they can either slow down and annihilate in the plasma or escape beyond, most of them are stopped and annihilate in the very dense (~100-1000 H cm^{-1}) warm outer shells of the molecular clouds that lie within R<1.5 kpc. The disk positrons, on the other hand, are produced about equally in the warm HI gas and the hot superbubbles, which blow out into the halo. We calculate that roughly half of the disk positrons, which either stream through the low density (~0.1 H cm^{-1}) neutral HI at close to c, or diffuse through the hot superbubble plasma, escape into the overlying halo before they can stop and annihilate in the low density (0.3-3 H cm^{-1}) photoionized outer shells of clouds and superbubbles in the disk.

Thus, we have shown that not only the measured 511 keV luminosity bulge/disk ratio but also the measured positronium fraction and the measured broad/narrow 511 keV line emission, can **ALL** be fully explained by positrons from the decay of radionuclei made by explosive nucleosynthesis in supernovae, if the propagation of these relativistic positrons in the various phases of the interstellar medium is taken into account. Moreover, we predict that within the positron bulge (<1.5 kpc), the broad and narrow components of the 511 keV line each essentially come from separate and potentially resolvable regions. We predict the line with from flux within the inner 0.5 kpc of the Galaxy and the Galactic Disk (1.5–8 kpc) will be narrow, while that from 0.5 to 1.5 kpc will be broad.

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