Galactic Positron Annihilation: A Misteriosa Solved

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INTEGRAL/SPI Galactic 511 Line Distribution (Weidenspointner et al. 2007)
The Mysteries That Never Really Existed

Mystery: The Bulge-to-Disk ratio of the annihilation radiation is ~4 times that of the Bulge-to-Disk ratio of the positron production distribution expected from Bulge and Disk components of Supernova Ia and Ip’s and Core Collapse SNIIIs.

Solution: Positron are emitted in radionuclide decay with relativistic energies, and propagate kiloparsecs until they either escape into the Halo or encounter the HII or HI gas of the outer portions of molecular clouds.

Result: Bulge-to-disk ratio agreement,
Positronium fraction agreement,
511 keV broad-to-narrow line width agreement
Disk asymmetry explained by the Galactic spiral arm structure
No unexplained signal for signal of Dark Matter decay/annihilation
Spectral Signatures -- Lines in Physics and Astrophysics: Atomic Lines

Emission lines identify the elements at cosmic distances

Absorption lines yield redshifts of intervening clouds and chemical composition

Also, thermal and Doppler broadening, Doppler shifts of centroid, Zeeman splitting, and many many more uses of atomic lines.

8/31/09

ESAC/Madrid August 27, 2009
Lines in Physics and Astrophysics: Nuclear Lines

In astrophysics nuclear lines result from radioactive decay of isotopes created in stars and explosive nucleosynthesis.

Neutron activation and subsequent decay identifies chemical composition of samples
Other Types of “Lines” in Physics and Astrophysics

Cyclotron Resonant Scattering Features, “cyclotron lines”

21 cm spin-flip line from hydrogen

Electron/Positron Annihilation “Line”
Discovery of Cosmic Line Radiation -- 1972

If the identification of the statistically deviant points as evidence for a spectral line is correct, the present results may constitute the first detection of a γ-ray spectral line from a celestial source. Not only are gamma lines a direct observational link between nuclear physics and astrophysics, but they also have various astrophysical and cosmological implications, depending on their energy; and the possibility of nuclear spectroscopy of astronomical objects is most intriguing.
Nuclear Line Astrophysics

Nuclear line fluxes, energies, and widths have been predicted since the 1950s (Morrison, Arnold, Chupp, Burbidge et al., Arnett, Ramaty & Lingenfelter, Clayton et al.)

Detections only began in the late 1970s from balloons (Leventhal et al. 1980) and the early 1980s from satellites (Mahoney et al. 1984)

$^{26}$Al Line from Mahoney et al. 1984

511 line from Leventhal, McCallum, & Stang 1980

8/31/09 ESAC/Madrid August 27, 2009
Nuclear Line Astrophysics (con’t)

Validates the concept of nucleosynthesis in stars and explosive nucleosynthesis in supernovae.

Isotope mass estimates plus simulations of explosions of various mass stars add to understanding of explosions and stellar evolution.

Galactic distributions and intensity tell about supernova rates, spatial distributions, the ISM, and propagation properties of various phases of the ISM.

Radioactive isotopes power the luminosity of supernova outbursts over time.

Two of these (plus $^{26}$Al) are the same isotopes responsible for positron production.
Calculation for the Source and Distribution of 511 keV radiation in the Galaxy

- Galactic Supernova Rates vs Supernova Type
- Sites of Supernova Events
- Isotope Production in Various Types of Supernova
- Escape Fractions for Isotopes from Remnant Ejecta
- Properties of the Various Interstellar Media (Temperature and Density)
- Propagation of “MeV” positrons (Interactions with Magnetic Fields)
- Need to “Thermalize” (Energy < 10 eV) before Annihilation
- Molecular Cloud Distribution and Structure

But, first, the measurements by INTEGRAL
The Spectrometer on INTEGRAL (SPI)

Coded Mask

### Facts and figures about the spectrometer

<table>
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<th>Value</th>
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<td>Diameter</td>
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<td>Power</td>
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<tr>
<td>Telemetry</td>
<td>22 kb/s</td>
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<tr>
<td>Field of View</td>
<td>16°</td>
</tr>
<tr>
<td>Energy range</td>
<td>20 keV - 8 MeV</td>
</tr>
<tr>
<td>Resolution</td>
<td>3 keV at 1.33 MeV</td>
</tr>
</tbody>
</table>
| Sensitivity    | $3 \times 10^{-6}$ photon / cm²·s at 1 MeV  
|                | $2 \times 10^{-5}$ photon / cm²·s at 511 keV |
Early Results on the 511 keV Flux

The first 8.9 Ms accumulated in 2004

The Positron Annihilation Line Distribution from INTEGRAL/SPI

Galactic 511 keV longitude and latitude distribution from INTEGRAL/SPI (Knödlseder et al. 2005)

Fitting of spherical shells and a disk has led to excellent data that can form the basis for understanding why the positron distribution is as is observed (Knödlseder et al. 2005; Weidenspointner et al. 2007).
The INTEGRAL/SPI Data

- Spherical bulge of radius 1.5 kpc
- Disk of half height = 400 pc extends at least to the Solar distance (8 kpc)
- Spherical Halo extending beyond 1.5 kpc

1 Year (Knodlseder et al. 2005)
- $L_x(B) = 0.74 \pm 0.04 \times 10^{43}$ photons/s
- $L_x(D) = 0.26 \pm 0.07 \times 10^{43}$ photons/s
- $L_x(Bulge)/L_x(Disk) \approx 3.0 \pm 0.8$

2 Years (Weidenspointner et al. 2007)
- $L_x(B) = 0.60 \pm 0.05 \times 10^{43}$ photons/s
- $L_x(D) = 0.36 \pm 0.09 \times 10^{43}$ photons/s
- $L_x(Bulge)/L_x(Disk) \approx 1.7 \pm 0.5$
The INTEGRAL/SPI Data (con’d)

- Narrow Spheroidal Gaussian (3° FWHM or 0.4 kpc @ 8kpc)
- Wide Spheroidal Gaussian (11° FWHM or 1.5 kpc)
- Disk of half height = 400 pc extends at least to the Solar distance (8 kpc)

> 4 Years (Weidenspointner et al. 2008)
- \( L_x(B) = 0.57 \pm 0.08 \times 10^{43} \) photons/s
- \( L_x(D) = 0.40 \pm 0.06 \times 10^{43} \) photons/s
- \( L_x(B+H) = 1.55 \pm 0.1 \times 10^{43} \) photons/s
- \( L_x(H) \approx 1 \times 10^{43} \) photons/s
- \( L_x(\text{Bulge})/L_x(\text{Disk}) = 1.4 \pm 0.3 \)

- Total Galactic 511 keV Luminosity = \( 2.0 \pm 0.2 \times 10^{43} \) photons/s
More INTEGRAL/SPI Data

Positron Annihilation via Positronium

Direct Annihilation on free and bound electrons --> 2 photons
Indirect Annihilation via Positronium formation --> 2 or 3 photons

Positronium forms in singlet state (parapositronium) 25%, yields 2 511 keV photons
Positronium forms in triplet state (orthopositronium) 75%, yields 3 photons

INTEGRAL/SPI measurements of 2 photon line flux to 3 photon continuum in the bulge and disk implies that the bulk of the positrons annihilate via positronium:

\[ f_{Ps} = 94\pm6\% \quad \text{Churazov et al. 2005} \]
\[ f_{Ps} = 92\pm9\% \quad \text{Weidenspointner et al. 2006} \]
\[ f_{Ps} = 95\pm3\% \quad \text{Jean et al. 2006} \]
\[ <f_{Ps}> = 94\pm4\% \]

In the halo, the fraction depends upon the refractory grain abundance. Jean et al. (2006) estimate 18%-42%
Conversion of Luminosity to Positron Annihilation Rate

\[ A = \left( \frac{e^+}{\gamma_{511}} \right) \times L_x \quad \text{and} \quad e^+ / \gamma_{511} = \left[ 2(f_{Ps}/4) + 2(1-f_{Ps}) \right]^{-1} \]

\[ e^+/\gamma_{511} \text{ (Bulge and Disk)} = 1.69\pm0.17 \quad e^+/\gamma_{511} \text{ (Halo)} = 0.65\pm0.7 \]

From the positronium fraction, we can calculate the ratio of positrons to 511 keV photons, and from that, the inferred annihilation rate.

Using 2 year data:

\[ A_B = 0.96\pm0.17 \times 10^{43} \text{ e}^+/s \]
\[ A_D = 0.68\pm0.12 \times 10^{43} \text{ e}^+/s \]
\[ A_H = 0.65\pm0.11 \times 10^{43} \text{ e}^+/s \]

Total Galactic Positron Production Rate = \(2.3\pm0.3 \times 10^{43} \text{ e}^+/s \) as inferred from the 511 keV line and positronium measurements.
Another INTEGRAL/SPI Measurement

511 keV Line Width

Width depends upon temperature of the medium and its ionization state, which affects the fraction of positronium formed by charge exchange with H, H₂, and He.

Prompt annihilation of fast moving positronium: \( \Delta E = 6 \text{ keV FWHM} \)

Thermal annihilation of slower positronium or direct annihilation: \( \Delta E < 2 \text{ keV} \)

Annihilation in hot, tenuous medium may yield a narrow line if annihilation occurs on refractory dust grains or broad line (~10 keV FWHM) with hot, fast electrons.

INTEGRAL/SPI fits the 511 line was resolved into a broad line and a narrow line (Churazov et al. 2005; Jean et al. 2006)

\[ 67 \pm 10\% \text{ narrow (1.3} \pm 0.4 \text{ keV)} \quad 33 \pm 10\% \text{ broad (5.4} \pm 1.2 \text{ keV)} \]

Broad/narrow ratio ~0.5
What about the Bulge-to-Disk Ratio of Galactic supernovae?

• SNIa and SNIp contribute ~85% of annihilating positrons.

• Assume SNIa occurrence rate is the same for all galaxies when expressed as SNe per year per unit of blue luminosity of parent galaxy (Cappellaro et al. 1999)

• We conclude that the time-averaged bulge/disk ratio of Galactic SNIa and associated SNIp is 0.25, using the stellar bulge-to-disk blue luminosities from Simien & de Vaucouleurs (1986).

• After taking into account star burst SNae in the bulge (30% extra or 0.08), the bulge/disk ratio implied from supernovae is 0.33.

Thus the Mystery!
The stellar distribution estimate of positron production of 0.33 is very different from that measured for annihilation at 1.4±0.3.
Temporal Variation of Galactic Supernovae

The Milky Way inner bulge region contains a bar-like gravitational asymmetry.

The “bar” causes gas to fall into the center and triggers a round of star formation.

We expect $2.5 \times 10^5$ SNIa from the burst, or an added 0.08 SNIa per 100 yr.

This increases the bulge/disk production ratio to ~0.42. Still a factor of three different from the observed annihilation ratio $1.4\pm0.3$.

The solution to the problem is to consider the propagation of the positrons from the SNae to the annihilation sites as a function of ISM phase experienced.
Outline of Approach to Solving the “Problem”

- Production of positrons by supernovae (isotopes, SNa type, rates)
- Spatial distribution of positron production
- Scattering and propagation of relativistic positrons vs ISM phase
- Slowing down of positrons in various phases of the ISM
- Annihilation in the various phases of the ISM
- Results and comparison to observations
What happens in the Bulge, stays in the Bulge!
(Well, maybe 20% get into the Halo)
Production of Positrons by Galactic supernovae

• Major sources of positrons are decay chains of $^{56}\text{Ni}$, $^{44}\text{Ti}$, and $^{26}\text{Al}$, all produced in explosive nucleosynthesis in supernovae

• Production depends upon Mass Yields, SNae occurrence rates, and survival fraction of positrons in supernova ejecta as it expands into the ISM

$^{26}\text{Al} \rightarrow ^{26}\text{Mg}$

Positrons 82% of decays; 1.04 x $10^6$ yr mean life, ejecta long gone, 100% survival

Direct observation of 1.809 MeV line yields steady state mass 2.8±0.8 $M_{\odot}$ of $^{26}\text{Al}$

This implies a positron production rate of

$Q_{26} = 0.3\pm0.1 \times 10^{43} \text{ e}^+/\text{s}$

$^{26}\text{Al}$ line at 1.809 MeV (Diehl et al. 2006)
$^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$

$e^{-}$ capture (8.8 d) $\rightarrow e^{+}$ emission (19%; 111.4 d)

Would exceed Galactic production rate if all positrons escaped the ejecta.

Most lose energy and annihilate unobserved in dense ejecta (i.e., they power the supernova remnant!)

$\text{SNIa} \rightarrow 0.58 M_{\text{solar}}$ (Nomoto, Thielemann & Yoko 1984)

$\text{SNIp} \rightarrow 0.44 M_{\text{solar}}$ (Woosley, Taam & Weaver 1986)

$\text{SNIbc} \rightarrow 0.16 M_{\text{solar}}$ (Woosley & Weaver 1995)

$\text{SNII} \rightarrow 0.08-0.10 M_{\text{solar}}$ (Rauscher et al. 2002)

Expected $e^{+}$ production rate $Q_{56} = 75 \times 10^{43} f_{56} \nu_{\text{Ia}} e^{+}/s$

$f_{56}$ is the mean survival fraction of positrons from $^{56}\text{Co}$ decay

$\nu_{\text{Ia}}$ is Galactic SNIa rate in SN/100 years
$^{44}\text{Ti} \rightarrow ^{44}\text{Sc} \rightarrow ^{44}\text{Ca}$

e$^-$ capture (89 yr) $\rightarrow$ e$^+$ emission (95%; 5.7 yr)

Long $^{44}\text{Ti}$ decay mean life means essentially all (>97%) survive in ejecta

Solar $^{44}\text{Ca}/^{56}\text{Fe} = 1.23 \times 10^{-3}$ allows us to calculate the production rate from $^{44}\text{Ti}$ in terms of the SNIa rate

Assuming 1/2 of Galactic $^{56}\text{Fe}$ is produced by SNIa (Timmes, Woosley & Weaver 1995)

$$Q_{^{44}\text{Ti}} = 1.2 \times 10^{43} \nu_{\text{Ia}} \text{ e}^+ / \text{s}$$

The total production rate of positrons in the bulge and disk from iron nucleosynthesis in Galactic supernovae is

$$Q_{\text{B+D}} = (75 \ f_{^{56}\text{Fe}} \ \nu_{\text{Ia}} + 1.2 \ \nu_{\text{Ia}} + 0.3) \times 10^{43} \text{ e}^+ / \text{s}$$

Need estimates of $f_{^{56}\text{Fe}}$ and $\nu_{\text{Ia}}$
Mean Supernova Rates in Our Galaxy

Estimated from 3 factors, based upon extragalactic observations

• type of supernova
• Hubble classification of the parent galaxy
• Galactic stellar blue-light luminosity

• Hubble classification of our Galaxy
• Milky Way = SB(r)bc pec  bc --> intermediate type Sc spiral, B --> stellar bar
  pec --> Galaxy is cannibalizing a small satellite galaxy

Rates: 1 S Nu = SN/100 yr x h₀² L_{Gal}^{BL}

For the Milky Way: SNIa=0.43±0.16, SNIp=0.05±0.02, SNIbc=0.27±0.13, SNII=1.63±0.67

Total rate of about 1 every 45 years (2.30±0.70 S Nu)
Positron Production Summary

Total Positron Production in Galaxy: $2.3 \pm 0.2 \times 10^{43} \text{ e}^+/s$ (from observations)

Insert $v_{\text{Ia}} = 0.43\pm0.16$ per 100 years,

$$Q_{B+D} = \left[ (32\pm13) f_{56} + (0.5\pm0.2) + (0.3\pm0.1) \right] \times 10^{43} \text{ e}^+/s$$

$\sim0.3 \times 10^{43} \text{ e}^+/s$ from $^{26}\text{Al}$

$\sim0.5 \times 10^{43} \text{ e}^+/s$ from $^{44}\text{Ti}$

$\sim1.5 \pm 0.3 \times 10^{43} \text{ e}^+/s$ from $^{56}\text{Ni}$, if they have a survival fraction of $5\pm2$

$2.3\pm0.2 \times 10^{43} \text{ e}^+/s$

The survival fraction of $\sim5\%$ was calculated by Chan & Lingenfelter (1993) and is consistent with $3.5\pm2\%$ inferred from SNIa light curves (Milne, The, & Leising 1999, 2001).

Thus, the entire positron production required can originate in the iron nuclei explosive nucleosynthesis from Galactic supernovae with no free parameters.
Positron Energy Considerations vis-a-vis Distribution

The great bulk of surviving and escaping positrons are relativistic (~0.7c; Chan & Lingenfelter 1993).

In order to annihilate with an observable 511 keV line, the positrons must be decelerated to energies ≤10 eV.

Positronium formation via charge exchange with H, H₂, and He in flight at the orbital speed of the bound electron yields a fast moving “atom” which decays yielding a broad component (~6 keV) to the 511 keV line.

Positronium formation or direct annihilation with free electrons occurs at lower thermal energies and thus the line width is smaller (~2 keV).

The distance traveled during the slowing down process can be substantial.

Therefore the spatial distribution of positron annihilation may be very different than that for the production.
Thermalization

Energy loss is by ionization losses in the ejecta and the ISM
Thermalization requires \(\sim 0.12 \text{ g/cm}^2\)
Range \(n d_{sd} \sim 6 \times 10^{22} \text{ H cm}^{-2}\) in neutral gas, with the range reduced by \((1 + x_e)^{-1}\) if the gas is ionized

Slowing down distance \(d_{sd} \sim 20/n(1+x_e) \text{ kpc}\), where \(n\) is the mean H density in cm\(^{-2}\)

Average velocity \(\beta c \sim 0.7 \sim 0.22 \text{ pc/yr}\)

Slowing down time \(t_{sd} \sim d_{sd}/ \beta c \sim 9 \times 10^4/n(1+x_e) \text{ yr}\)

The slowing down distance for a given phase of the ISM tells us if the positrons will annihilate locally or if they will escape into another phase or region of the Galaxy.
How far will the Positrons Go?

Slowing down distance:

- > 0.5 kpc in $n \sim 40 \text{ cm}^{-3}$ molecular clouds
- > 50 kpc in warm medium with $n \sim 0.4 \text{ cm}^{-3}$
- > 3 Mpc in hot phases with $n \sim 3 \times 10^{-3} \text{ cm}^{-3}$

All positrons would escape the Galactic disk and bulge before slowing down, unless there were a mechanism to efficiently limit their travel!

We propose that turbulence is the answer in the ionized phases and intercepting molecular clouds in the neutral phases.
What is a Humble Experimentalist to do?

The current understanding of charged particle propagation assuming Larmor resonance scattering as expressed by Wentzel in his review article in 1974.

Diffusion on the scale of the Larmor radius only occurs in very turbulent regions, such as shocks in young supernova remnants (Uchiyama et al. 2007).

Such intense plasma turbulence is highly localized and short lived, and not applicable to the diffuse ISM where the mean turbulence is far weaker.

Direct observations of cosmic ray electrons and positrons extending to MeV and lower energies (e.g., Fan et al. 1968) and synchrotron radio emission from the Galactic halo (e.g., Syrovatskii 1959) require diffusion mean free paths greater than a parsec, implying a stopping distance greater than a kiloparsec.
A Simple Concept

\( r_L \) = Larmor radius
\( \lambda \) = diffusion mean free path
\( d_{SD} \) = stopping path distance due to ionization losses only
\( l_{SD} \) = mean stopping length when diffusion is considered

\[ l_{SD} \sim (d_{SD} \cdot \lambda)^{1/2} \]

Now we just need to estimate \( d_{SD} \) and \( \lambda \).

We assume charged particle propagation along magnetic flux tubes
Dominated by resonant pitch angle scattering by cascading MHD waves at \( r_L \)
Propagation Amongst Turbulence

\[ \lambda \sim \frac{r_L}{(\delta B_L^2/B_0^2)}, \] where \((\delta B_L^2/B_0^2)\) is the scattering probability

and in turn,

\[ (\delta B_L^2/B_0^2) \sim (\delta B_t^2/B_0^2) \times \left(\frac{r_L}{l_0}\right)^{2/3} \]

where

\((\delta B_t^2/B_0^2)\) is the relative energy density in the MHD waves at \(r_L\) compared to that in the total magnetic field, and

\(\left(\frac{r_L}{l_0}\right)^{2/3}\) is relative energy in the MHD Kolmogorov cascade spectrum at \(r_L\) compared to that at the initial turbulent scale, \(l_0\)
Galactic Bulge

Hot, ionized (kT \sim 10^7 K), tenuous (n \sim 0.005 \text{ H cm}^{-3}), B_0 \sim 10 \mu\text{Gauss}, \text{Size} \sim 3 \text{kpc}

\[ d_{SD} \sim 3-30 \text{ Mpc but } r_L \sim 10^{-10} \text{ to } 10^{-9} \text{ pc} \]

\[ (\delta B_t^2/B_0^2) \sim 10^{-2}, \text{ since } B_0^2 \sim (10^{-5})^2/8\pi \sim 10^{-11} \]

and \[ \delta B_t^2 \sim 1000 \text{ SNIa per } 10^6 \text{ yr or } 10^{54} \text{ ergs in a volume of } \sim 3 \text{kpc FWHM, or } \sim 10^{-13} \text{ erg cm}^{-3} \]

\[ (r_L/l_0)^{2/3} \sim (2-7) \times 10^{-8}, \text{ since } l_0 \sim 50 \text{ pc (Yan \& Lazarian, 2004), comparable to SNIa SNR’s, and } r_L \text{ given above} \]

Thus, the relative energy density in the MHD waves at \( r_L \) compared to that in the total magnetic field

\[ (\delta B_L^2/B_0^2) \sim (2-7) \times 10^{-10}, \text{ and } \lambda \sim r_L/(\delta B_L^2/B_0^2) \sim 0.2-5 \text{ pc} \]

Thus positrons travel a mean distance in the Galactic Bulge of

\[ l_{SD} \sim (d_{SD}*\lambda)^{1/2} \sim (3-30 \text{ Mpc x 0.2-5 pc})^{1/2} \sim 1 \text{ to } 10 \text{ kpc} \]
Consequences of Kiloparsec Propagation of Positrons in the Bulge

Positron will travel large distances in the hot plasma of the Galactic Bulge until they encounter molecular clouds where they stop and annihilate:

-- In the central 0.5 kpc of the Bulge (the Central molecular Zone)
-- In the surrounding Tilted Disk that extends ±0.8 kpc above and below the plane and ±1.3 kpc along the plane inclined at 29° to the plane

Molecular clouds in the Central Molecular Zone have an ionized HII outer shell extending over a neutral HI shell that covers the H$_2$ core and those in the Tilted Disk have only the neutral HI shell.

d$_{SD}$ for the outer layers is ~10 pc, which is comparable to the outer shell thickness.

Thus, the vast majority of positrons “born” in the Bulge annihilate in the outer shell of molecular clouds via positronium formation 94±4% of the time.
What about Positrons Born in the Disk?

Again, the Disk ISM is mostly hot and tenuous, so that the positrons generally escape into the Halo, or annihilate in molecular clouds in the Disk.

Hence, one arrives at a larger 511 keV annihilation line bulge-to-disk ratio as compared to the visible light distribution of the positron production.

And hence a solution to the “Misteriosa Radiación Gamma de la Via Láctea”.
Structure of the Galaxy and Phases of the ISM

Phases within R < 0.5 kpc:
- Very Hot Medium
- Hot Medium
- Warm Ionized HII
- Cold Neutral HI
- Cold Molecular H$_2$

Phases within Tilted Disk:
- Hot Medium
- Cold Neutral HI
- Cold Molecular H$_2$
- Very little HII
Summary of Positron Transport Modeling

We model interstellar MHD turbulence as a composite slab/two-dimensional turbulence following Bieber et al. 1996.

We use an analytic approximation of scattering mean free paths calculated for slab MHD turbulence employing a quasi-linear theory from Teufel & Schlickheiser 2002.

We then calculate the mean stopping length as compared to the slowing down distance in each phase of the ISM contained in the Central Molecular Zone, Tilted Disk, Outer Bulge, and Disk.

This determines whether or not a positron will escape a region or annihilate there.

Essentially all of the annihilations take place in warm HII or HI regions most notably in the outer shells of molecular clouds.

From our calculations, we estimate the fluxes from each region for comparison with INTEGRAL observations.
We calculate in each phase:

- Positron slowing down time before annihilation
- Positron 1-D diffusion mean free path or streaming speed along B field
- Mean escape time from typical length of magnetic flux
- Fraction of positrons annihilating before escaping
- Relative fractions of positrons escaping into each neighboring phase

From the resulting matrix, we calculate:

- Expected positron production, propagation, slowing down, and annihilation in each region.

From this we calculate:

- The line flux from the 5 spatial regions
- The bulge to disk ratio
- The line widths for the inner bulge, the tilted disk, the outer bulge, and disk
The Nuclear Bulge (R<0.5 kpc)
We expect nuclear bulge SNIa to occur in Central Molecular Zone, and 85% to occur in the very hot medium outside of the molecular clouds.
Nearly 100% of positrons will reach the photoionized HII outer shell of a molecular cloud and annihilate there. Almost none escape into Tilted Disk.

The Tilted Disk in the Middle Bulge (0.5<R<1.5 kpc)
We expect the SNIa and SNIp to occur in the tilted disk, and no massive stars implies no core collapse contributions to the positron production.

We expect all positrons born in hot medium to diffuse into clouds and annihilate in the HI shells.

The Outer Bulge (1.5<R<3.5 kpc)
We expect very little (9%) of the positrons born in the Outer Bulge to annihilate there. The remaining 91% escape roughly equally in to the Tilted Disk or out to the Halo or Disk beyond 3 kpc, and annihilate there.

The Disk (>3.5 kpc)
We expect only 50% of the positrons to annihilate in the Disk and the rest to escape into the Halo.
The Result of the Calculations (Part One)

511 keV flux from the bulge, disk, and halo (x $10^{-3}$ photons/cm$^2$ s):

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<th>Region</th>
<th>Calculation</th>
<th>INTEGRAL/SPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulge (&lt;0.5 kpc)</td>
<td>0.39 ± 0.10</td>
<td>0.38 ± 0.03</td>
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<tr>
<td>Bulge (0.5-1.5 kpc)</td>
<td>0.33 ± 0.07</td>
<td>0.41 ± 0.06</td>
</tr>
<tr>
<td>Disk (1.5-8 kpc)</td>
<td>0.91 ± 0.14</td>
<td>0.94 ± 0.16</td>
</tr>
<tr>
<td>Halo &amp; Bulge</td>
<td>2.32 ± 0.40</td>
<td>2.14 ± 0.11</td>
</tr>
<tr>
<td>Disk (-50°&lt;l&lt;0°)</td>
<td>~0.38</td>
<td>0.43 ± 0.05</td>
</tr>
<tr>
<td>Disk (+50°&gt;l&gt;0°)</td>
<td>~0.23</td>
<td>0.24 ± 0.05</td>
</tr>
<tr>
<td>Disk Ratio (-50°&lt;l&lt;0°)/ (+50°&gt;l&gt;0°)</td>
<td>~1.6</td>
<td>1.8 ± 0.4</td>
</tr>
</tbody>
</table>

Annihilation rate for the bulge, disk, and halo (x $10^{43}$ e$^+$/s):

<table>
<thead>
<tr>
<th>Region</th>
<th>Calculation</th>
<th>Inferred from INTEGRAL/SPI</th>
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<tbody>
<tr>
<td>Bulge (&lt;1.5 kpc)</td>
<td>1.04 ± 0.15</td>
<td>1.15 ± 0.16</td>
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<tr>
<td>Disk (1.5-8 kpc)</td>
<td>0.76 ± 0.11</td>
<td>0.81 ± 0.14</td>
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<tr>
<td>Halo &amp; Bulge</td>
<td>1.95 ± 0.28</td>
<td>1.86 ± 0.20</td>
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<tr>
<td>Bulge/Disk</td>
<td>1.4 ± 0.4</td>
<td>1.4 ± 0.3</td>
</tr>
</tbody>
</table>
The Result of the Calculations (Part Two)

The positronium fraction in the bulge, disk, and halo:

<table>
<thead>
<tr>
<th></th>
<th>Calculated</th>
<th>INTEGRAL/SPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulge (&lt;1.5 kpc)</td>
<td>$0.92 \pm 0.08$</td>
<td>$0.92 \pm 0.09$ Weidenspointner et al. 2007</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$0.94 \pm 0.06$ Churazov et al. 2005</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$0.95 \pm 0.03$ Jean et al. 2006</td>
</tr>
<tr>
<td>Disk (&gt;3.5 kpc)</td>
<td>$0.88 \pm 0.08$</td>
<td>???</td>
</tr>
<tr>
<td>Halo (&lt;1.5 kpc)</td>
<td>$0.65 \pm 0.7$</td>
<td>???</td>
</tr>
</tbody>
</table>

The ratio of broad to narrow line widths in the bulge and disk:

<table>
<thead>
<tr>
<th></th>
<th>Calculated</th>
<th>INTEGRAL/SPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulge (&lt;1.5 kpc)</td>
<td>$0.68 \pm 0.26$</td>
<td>$0.49 \pm 0.17$ Jean et al. 2006</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$0.47 \pm 0.20$ Churazov et al. 2005</td>
</tr>
<tr>
<td>Bulge (&lt;0.5 kpc)</td>
<td>$\sim 0$ (i.e. narrow)</td>
<td>???</td>
</tr>
<tr>
<td>Bulge (0.5-1.5 kpc)</td>
<td>$6 \pm 3$ (i.e. broad)</td>
<td>???</td>
</tr>
<tr>
<td>Disk (1.5-8 kpc)</td>
<td>$\sim 0.02$ (i.e. narrow)</td>
<td>???</td>
</tr>
</tbody>
</table>
What About the INTEGRAL Disk Asymmetry -- A New Positron Source?

Weidenspointner et al (2008) report that the inner disk distribution of the 511 keV line is asymmetric with respect to the Galactic Center.

The ratio of fluxes out to ±50° is measured to be 1.8±0.4

Is this evidence of the need for a new source of positrons?
The Galactic spiral arms, as determined from the study by Vallée et al. (2005), indicate that disk emission from the Norma arm can provide the enhanced flux seen on one side and not on the other.

Using our calculations for emission from the disk, we arrive at an asymmetric flux with a ratio of ±50° disk flux of $1.6±0.4$ vs $1.8±0.4$ observed.

Again, a new source of 511 keV line radiation is unnecessary once one considers the distribution of matter in the spiral arms as viewed from Earth.

New Source of Positrons? -- No!
What About a Dark Matter Signal in the 511 keV Distribution?

Dark Matter “Solution” to the Bulge-to-Disk ratio “mystery” invoked in Boehm et al. 2004 was the basis for 150 subsequent Dark Matter candidates.

Boehm et al. assumed the positrons did not propagate beyond a pc after “birth”.

We show that this assumption is not supported by long-standing data, does not yield the correct bulge-to-disk ratio, and also does not yield the measured positronium fraction.

Therefore no Dark Matter signal is needed to describe the origin of the positron annihilation radiation distribution seen by INTEGRAL.
Another Signal of Dark Matter?

The ATIC/HESS result of an excess of total electrons above 600 GeV and the PAMELA result of an increase in the positron fraction above a few GeV has lead to another spate of dark matter speculations.

Propagation of positrons/electrons produced in collisions of cosmic ray nuclides with interstellar gas plus propagation of positrons, this time from local pulsars, can account for both results, and no dark matter signal is required.

If the Dark Matter theorists are looking for truly anomalous behavior .......
Spain 0 - 2 United States

Altidore's goal leads U.S. to stunning upset

U.S.-Spain
Bob Bradley's men ended Spain's 35-game unbeaten streak.