The all-sky distribution of 511 keV electron-positron annihilation emission

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astro-ph/0506026

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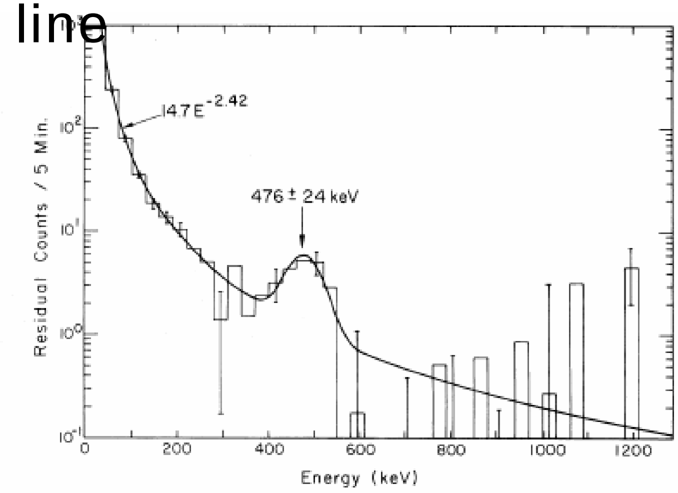
Masaki Mori, ICRR Group Internal Seminar, June 20, 2005

511 keV emission: basics

- Positrons from β^+–decay and μ^+–decay
  $\Rightarrow$ Most of them stops before annihilation
  Ex. 5 MeV e^+: m.f.p. $3g/cm^3 \rightarrow \sim 10^{24} e^-$
  $\sigma_{ann} \sim \sigma_{Thompson} / \gamma = 5 \times 10^{-26} cm^2$
  i.e. only ~5% decay before stop
- $e^+ + e^- \rightarrow \gamma + \gamma$
  $E = mc^2(1+\gamma)(1\pm\beta)/2 \sim 511$ keV ($\beta \sim 0$)
- Positronium decay (formed when $<10^6$K)
  $^1S_0$: ~25%, 1.25×10^{-10}s, $\rightarrow 2\gamma$
  $^3S_0$: ~75%, 1.5×10^{-7}s, $\rightarrow 3\gamma \rightarrow$ broader line
- First detection in 1973
  (Johnson and Haymes, balloon exp., ApJ184, 103)



OSSE observation

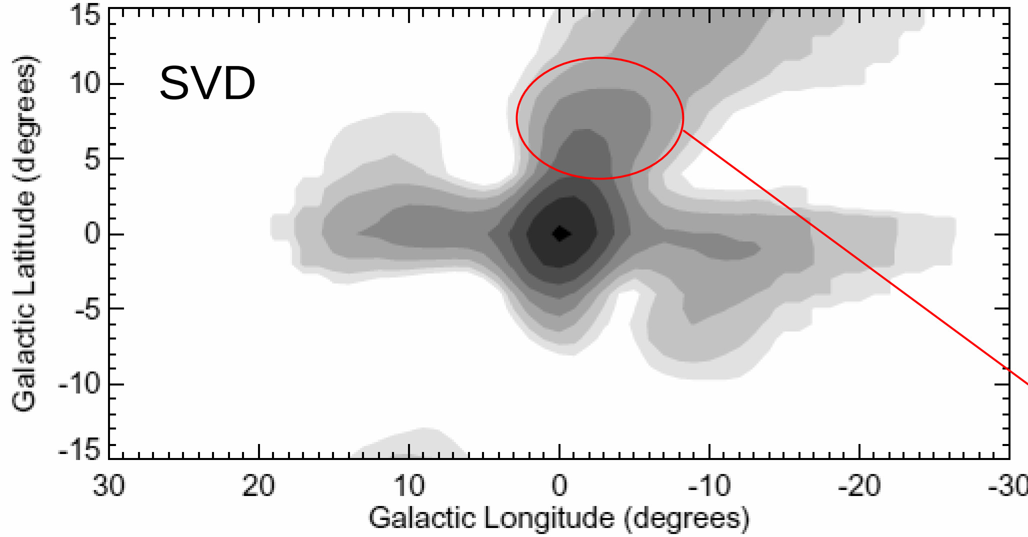


FIG. 5.—Map of the Galactic 511 keV positron annihilation line using the SVD method. Contours are exponentially spaced.

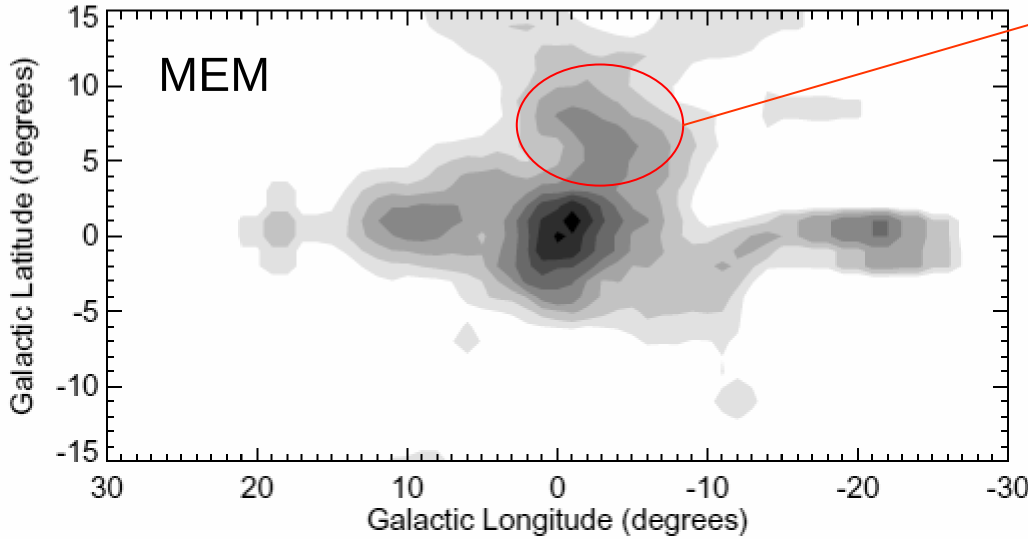


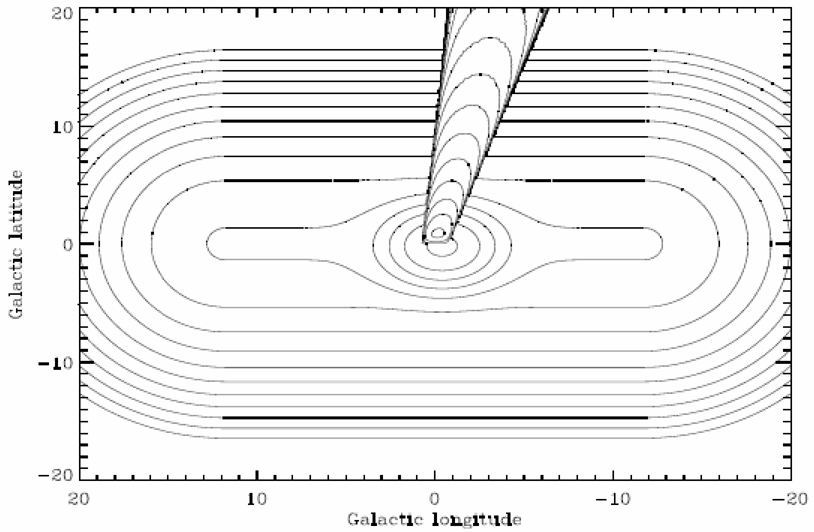
FIG. 6.—Map of the Galactic 511 keV positron annihilation line using the MEM. Contours are exponentially spaced.

Bulge + disk + PLE (positive latitude enhancement)

PLE ("annhilation fountain")

Purcell et al., ApJ 491 (1997) 725

“Annihilation fountain”



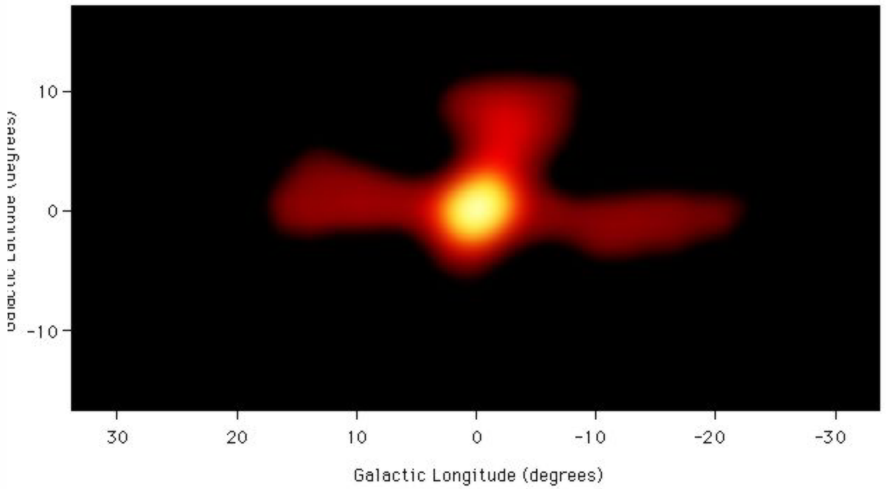


Fig. 2.— *Contour plot of the model annihilation emissivity of the Milky Way including the disk, galactic bulge, and fountain component. The contours are in units of* $10^{-(2+n)/5}$ *0.511 MeV ph cm*$^{-1}$ *s*$^{-1}$ *sr*$^{-1}$*, with the central contour corresponding to* $n = 1$.

“A starburst episode within the inner few hundred pc of our galaxy would drive hot pair-laden gas into the halo, with the one-sidedness pointing to the site of initial pressure release at the onset of the starburst activity.”

Dermer & Skibo, ApJ 487, 57 (1997)

INTEGRAL/SPIE

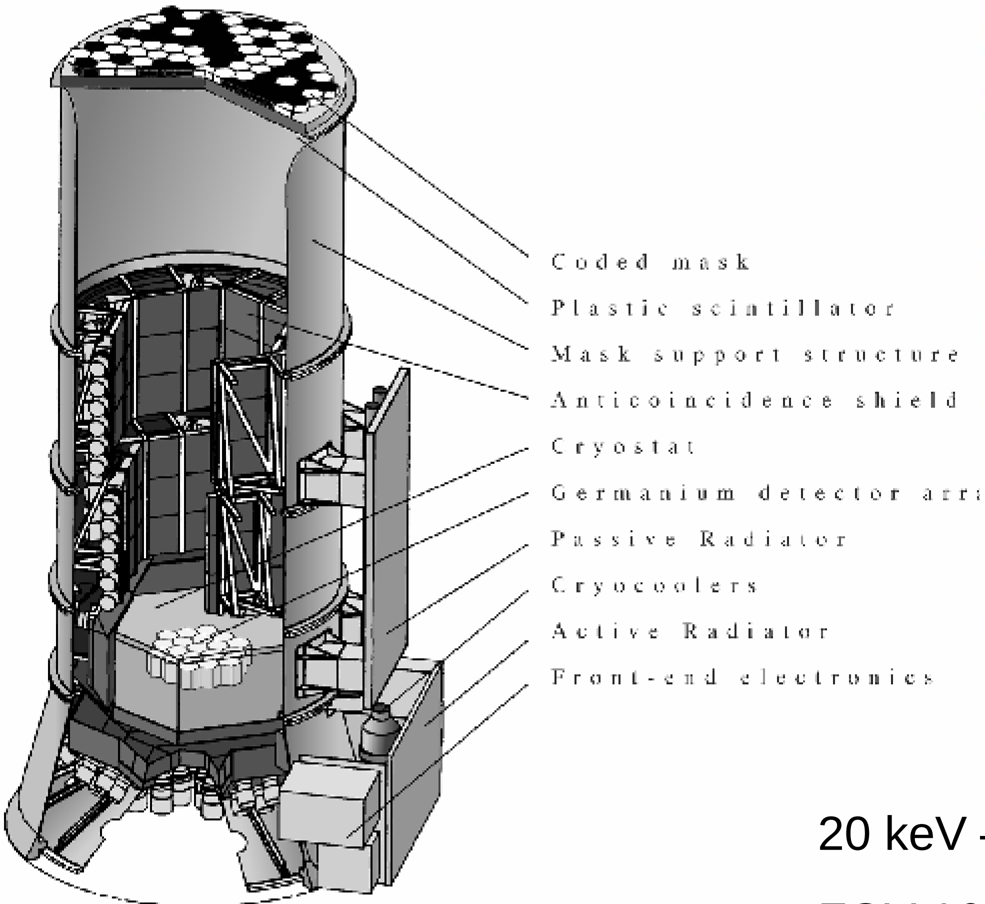


FIGURE 3 : Cutaway view of SPI and its subsystems

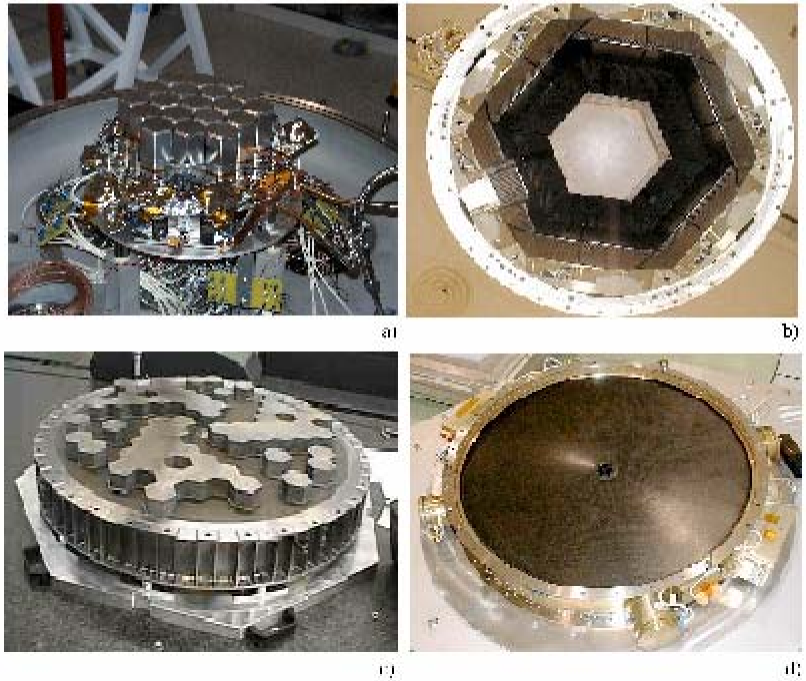


Fig. 3. View of some subsystems of the spectrometer: a) Ge array, b) ACS, c) mask, d) plastic scintillator.

20 keV – 8 MeV, 500 cm^2,

FOV 16deg, angular resolution 2.5deg,

Energy resolution 2.5keV@1.3MeV

SPI exposure

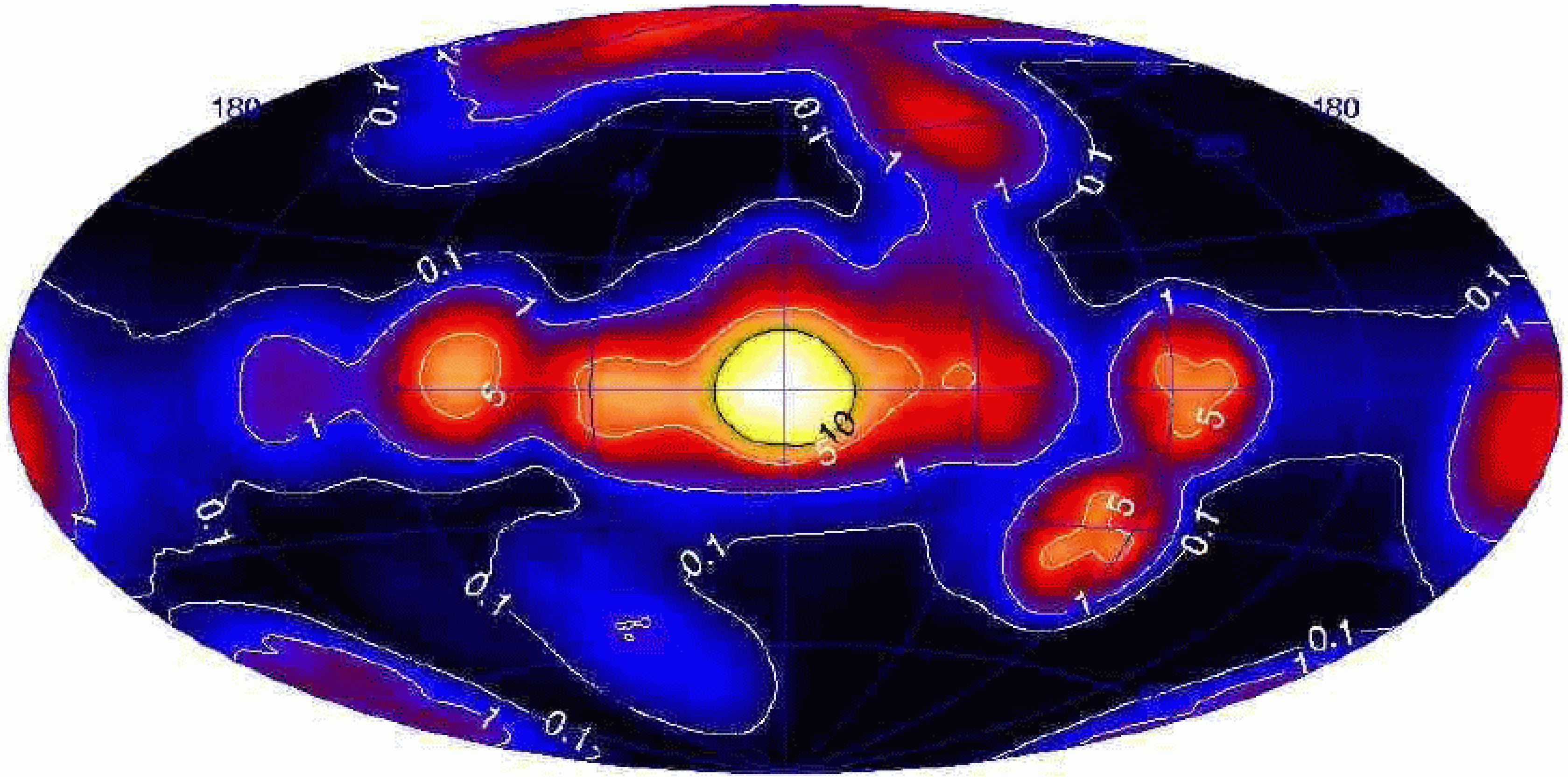


Fig. 1. Map of the effective SPI exposure at 511 keV for the dataset analysed in this work. The contours are labelled in units of 10^7 cm^2 s, corresponding to 13 ks (0.1), 133 ks (1), 667 ks (5), and 1.3 Ms (10) of effective exposure times.

Data: Dec 2002 – Oct 2003

Spectrum (not a topic today)

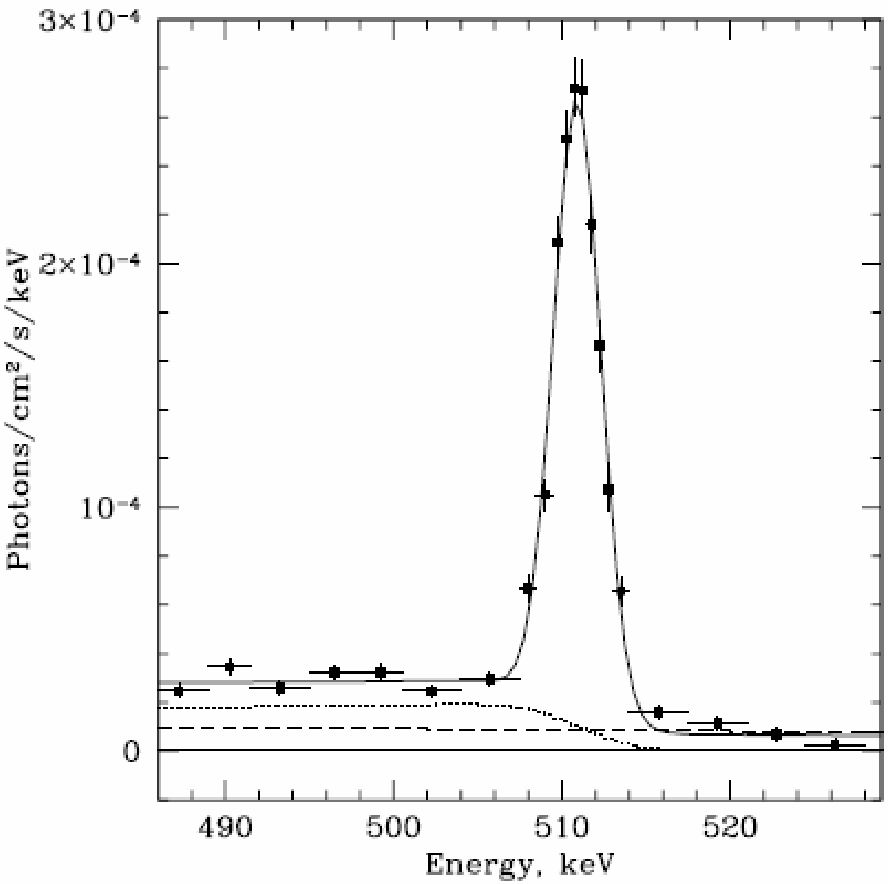


Figure 1. Spectrum of the e^+e^- annihilation radiation (fixed background model) detected by SPI from the GC region and the best-fitting model (thick solid line, see Table 1 for parameters). The dotted line shows the ortho-positronium radiation and the dashed line shows the underlying power-law continuum.

Table 1. Best-fitting parameters for the GC spectra calculated for a 6° (FWHM) Gaussian spatial model (the one-Gaussian plus ortho-positronium plus power-law models). Quoted errors are 1σ for a single parameter of interest.

	Model I Fixed background 485–530 keV	Model II Free background 450–550 keV
E_1 (keV)	510.988 [510.95–511.02]	510.954 [510.88–511.03]
FWHM_1 (keV)	2.47 [2.36–2.58]	2.37 [2.12–2.62]
$F_{2\gamma}$ (10^{-4} photon s^{-1} cm^{-2})	8.7 ± 0.20	7.16 ± 0.35
$F_{3\gamma}$ (10^{-4} photon s^{-1} cm^{-2})	45.6 ± 4.3	26.1 ± 5.7
$F_{3\gamma}/F_{2\gamma}$	5.2 ± 0.51	3.65 ± 0.82
F_{PS}	1.035 ± 0.023	0.94 ± 0.06
Power-law photon index α	2.0 (fixed)	2.0 (fixed)
χ^2 (d.o.f.)	151.2 (83)	192.7 (193)

Churazov et al., MNRAS 357, 1377 (2005)

Coded mask imaging

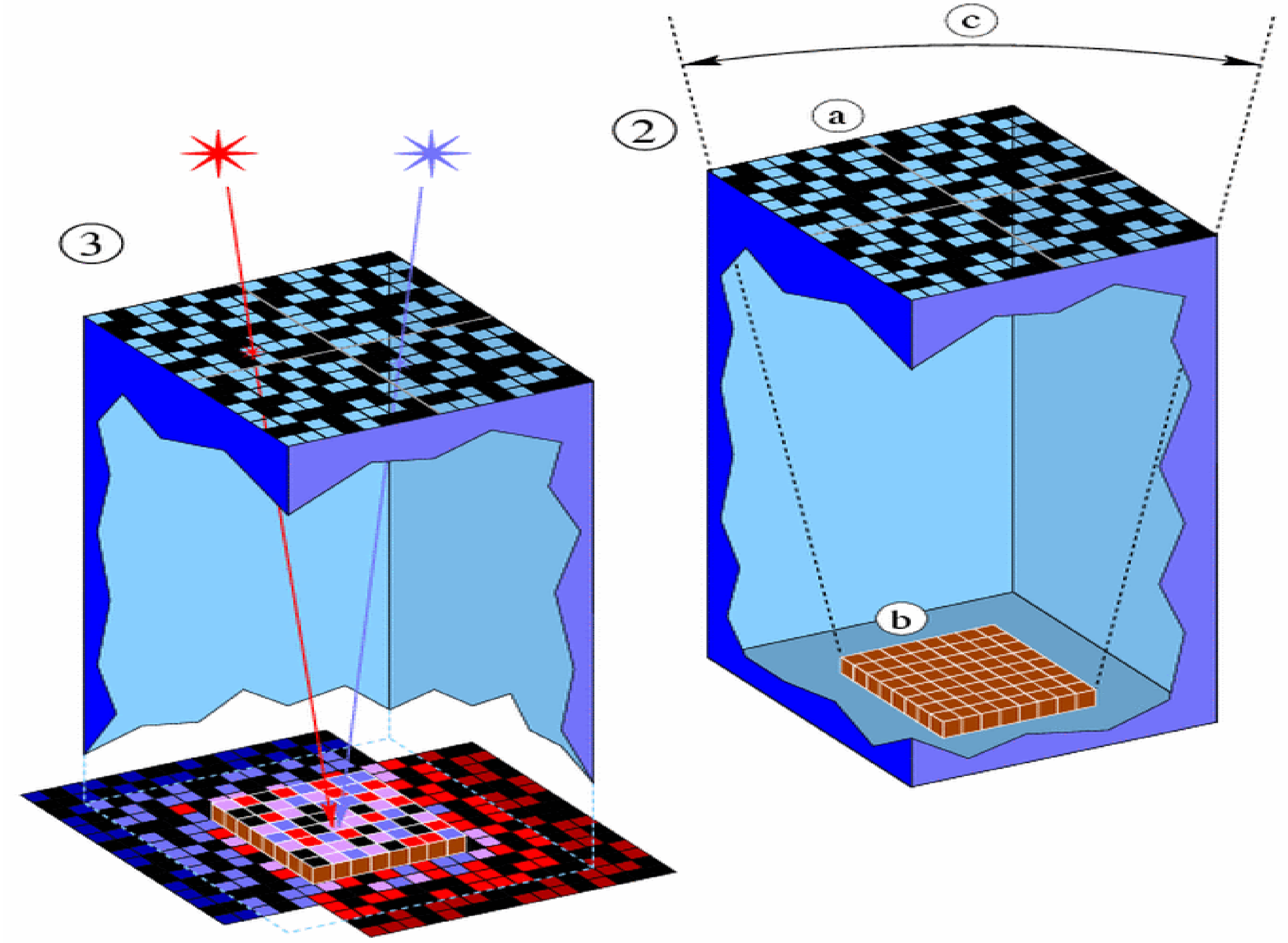


Image deconvolution

- Richardson-Lucy algorithm

$$f_j^{k+1} = f_j^k + \lambda^k w_j f_j^k \left(\frac{\sum_{i=1}^N \left(\frac{n_i}{e_i^k} - 1 \right) R_{ij}}{\sum_{i=1}^N R_{ij}} \right)$$

f_j^k : sky intensity
R_{ij} : instrumental response matrix
$e_j^k = \Sigma_j R_{ij} f_j^k + b_i$: predicted number of events
n_j^k : observed counts
b_i : instrumental background
λ_k : acceleration factor (Kaufman 1987)
$w_j = (\Sigma_j R_{ij})^{1/2}$: weight

511 keV map

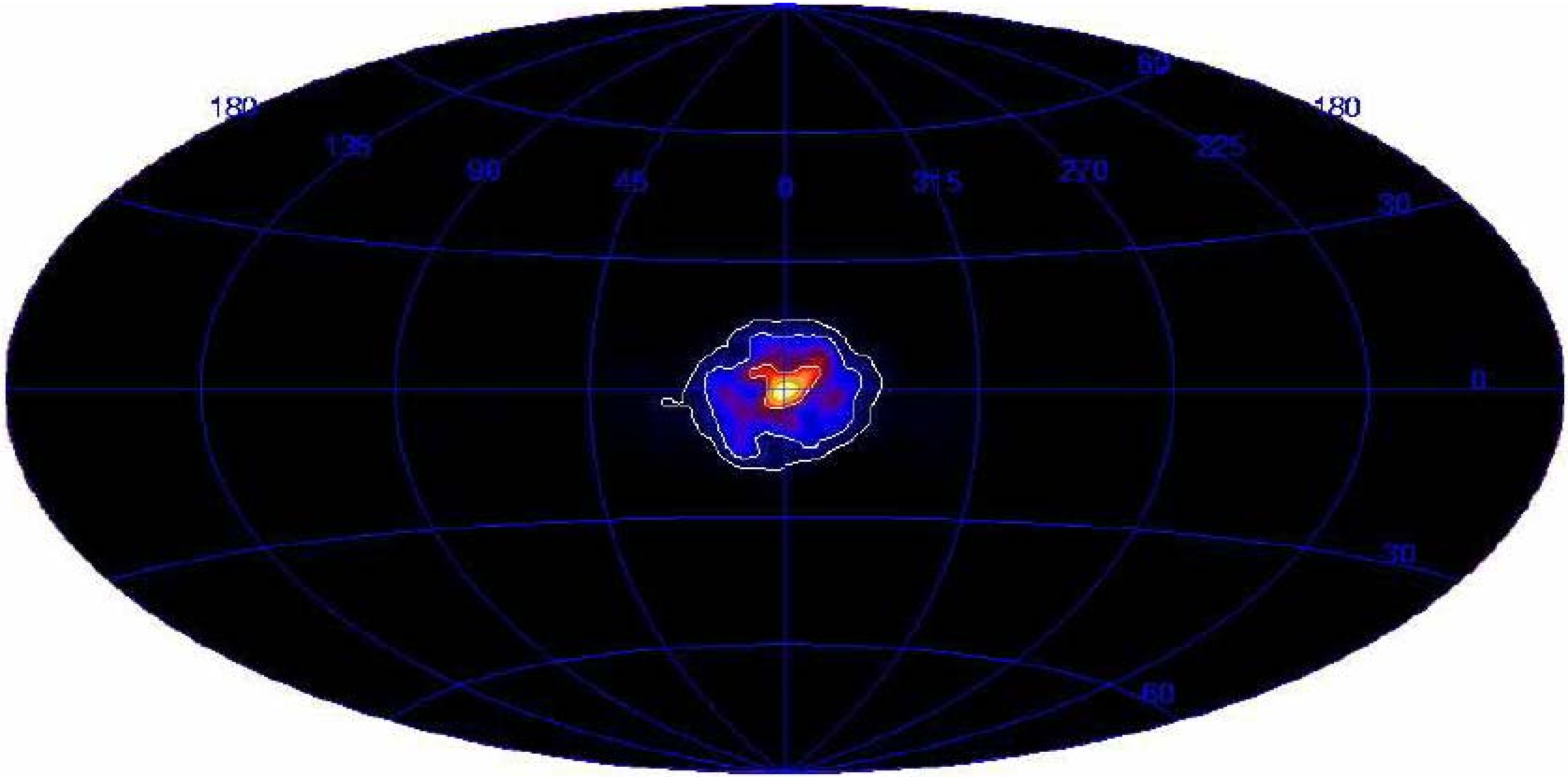


Fig. 4. Richardson-Lucy image of 511 keV gamma-ray line emission (iteration 17). Contour levels indicate intensity levels of 10^{-2}, 10^{-3}, and 10^{-4} ph cm^{-2}s^{-1}sr^{-1} (from the centre outwards).

511 keV map (2)

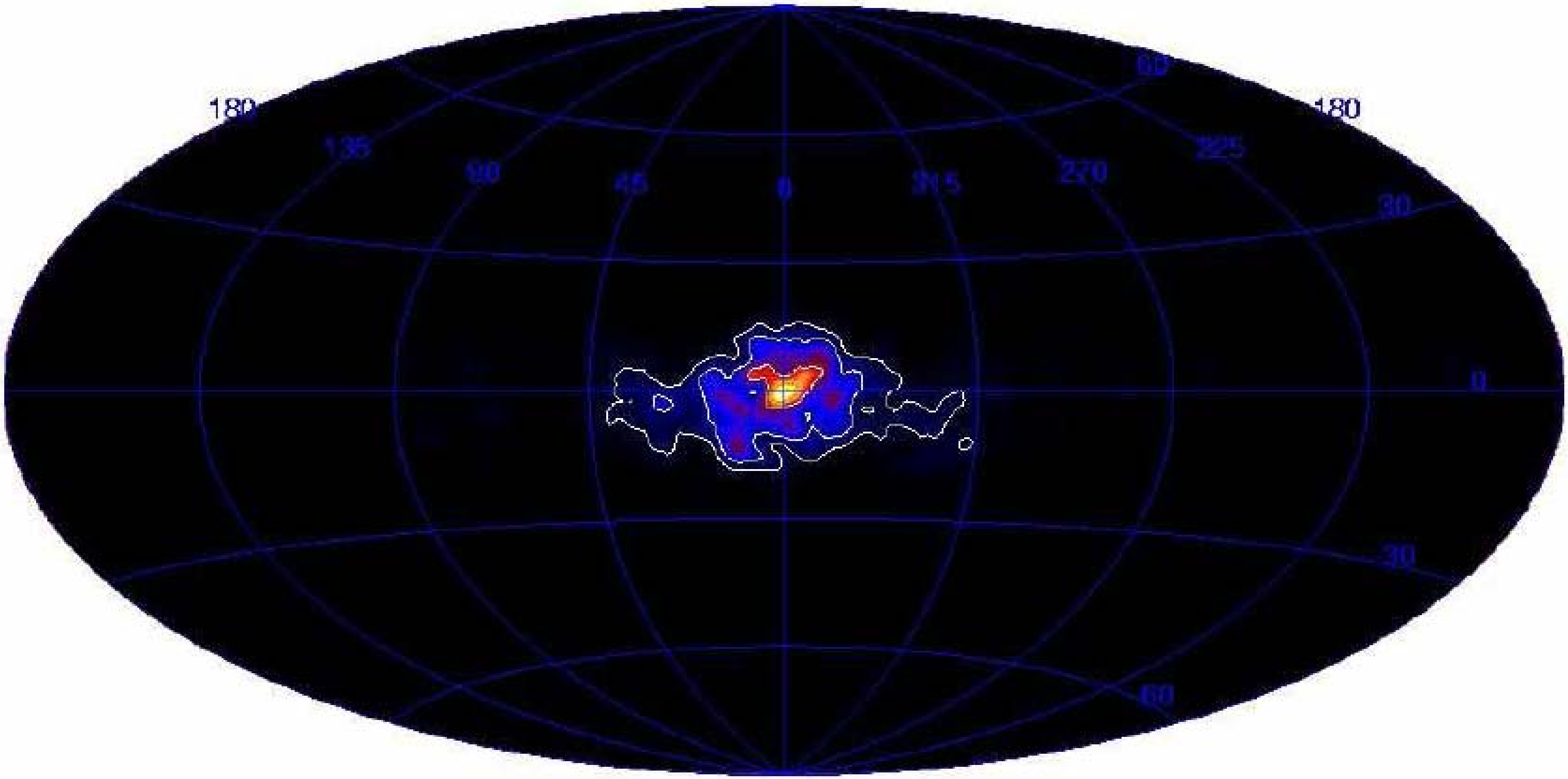


Fig. 6. Richardson-Lucy image after iteration 25. Contour levels are similar to Fig. 4.

511 keV profile

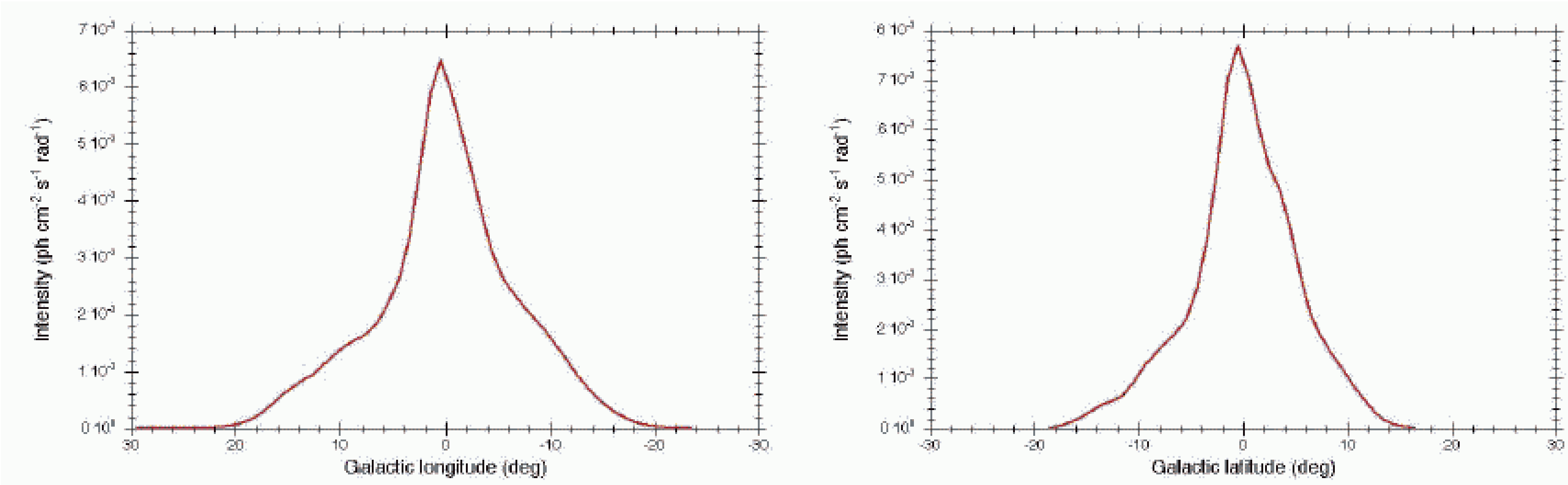


Fig. 5. Longitude and latitude profiles of the image shown in Fig. 4 (integration range $|l| \leq 30°$, $|b| \leq 30°$).

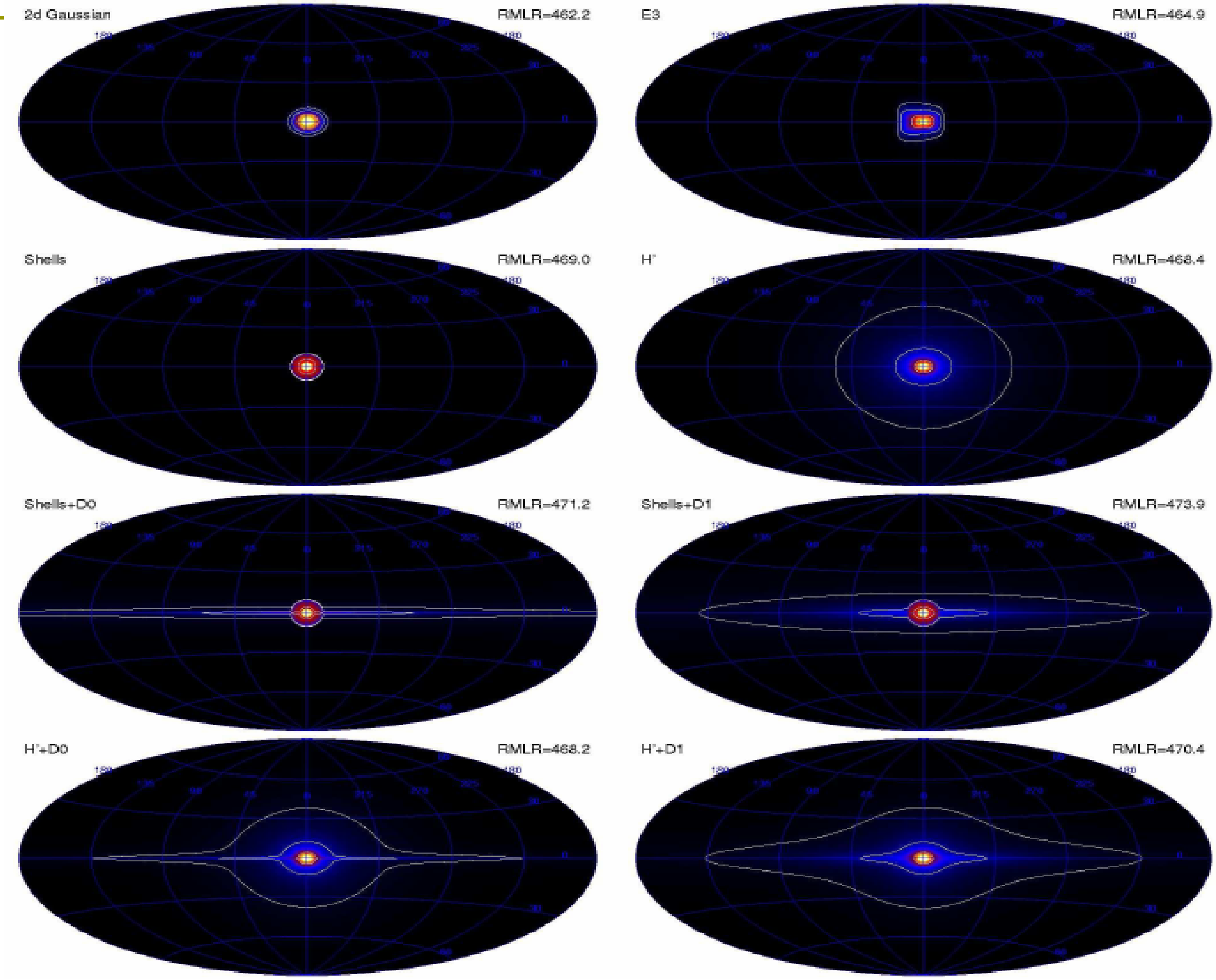
l_0-=-0.6deg, Δl-=8.1deg (FWHM)

b_0-=+0.1deg, Δl-=7.2deg (FWHM)

Flux: $(1.09 \pm 0.04) 10^{-3}$ ph/cm^{2}s

[|l|<30deg, |b|<30deg integration]

Model fitting



Model fitting results

Table 3. Summary of model fitting results. Fluxes are given as total 4π integrated all-sky values. Annihilation rates have been calculated assuming $f_p = 0.93$.

(positronium fraction)

Quantity	Bulge	Halo	Disk
Flux (10^{-3} ph cm^{-2}s^{-1})	1.05 ± 0.06	1.6 ± 0.5	0.7 ± 0.4
L_{511} (10^{43} ph s^{-1})	0.90 ± 0.06	1.2 ± 0.3	0.2 ± 0.1
L_p (10^{43} s^{-1})	1.50 ± 0.10	2.0 ± 0.5	0.3 ± 0.2
Total flux (10^{-3} ph cm^{-2}s^{-1})			$1.5 - 2.9$
Total L_{511} (10^{43} ph s^{-1})			$1.0 - 1.7$
Total L_p (10^{43} s^{-1})			$1.6 - 2.8$
B/D flux ratio			$1 - 3$
B/D luminosity ratio			$3 - 9$

Point source search (1)

Table 4. 511 keV narrow line 3σ upper flux limits for selected potential positron sources.

Source name	l (deg)	b (deg)	FWHM (deg)	3σ flux limit (10^{-4} ph cm^{-2}s^{-1})	Type of object
Sgr A*	0.00°	+0.00°	-	< 1.0	BHC
GRS 1758-258	4.51°	−1.36°	-	< 0.7	μQSO
Cyg X-1	71.33°	+3.07°	-	< 1.0	BHC
LS I+61°303	135.68°	+1.09°	-	< 3.3	μQSO
1E 1740.7-2942	359.15°	−0.12°	-	< 0.9	μQSO
Vela X-1	263.06°	+3.93°	-	< 1.1	HMXB
GX 5-1	5.08°	−1.02°	-	< 0.7	LMXB
GRS 1915+105	45.37°	−0.22°	-	< 1.0	LMXB
A 0620-00	209.96°	−6.54°	-	< 3.8	LMXB
Nova Muscae	295.30°	−7.07°	-	< 2.0	LMXB
Cir X-1	322.12°	+0.04°	-	< 1.1	LMXB
Cen X-4	332.24°	+23.89°	-	< 1.7	LMXB
GX 349+2	349.10°	+2.75°	-	< 0.8	LMXB
Sco X-1	359.09°	+23.78°	-	< 1.5	LMXB
Crab	184.56°	−5.78°	-	< 1.3	Pulsar
Geminga	195.13°	+4.27°	-	< 2.2	Pulsar
PSR J0737-3039	245.24°	−4.50°	-	< 3.0	Pulsar
Kepler	4.52°	+6.82°	-	< 0.7	SNR
Cas A	111.73°	−2.13°	-	< 1.9	SNR
Tycho	120.07°	+1.44°	-	< 2.0	SNR
SN 1987A	279.70°	−31.94°	-	< 1.0	SNR
SN 1006	327.58°	+14.59°	-	< 1.3	SNR
Lupus Loop	329.80°	+16.00°	-	< 1.3	SNR

Point source search (2)

Cygnus	79°	0°	5°	< 1.8	Star forming region (^{26}Al source)
Vela	265°	0°	5°	< 2.6	Star forming region (^{26}Al source)
Carina	286.5°	+0.5°	-	< 2.2	Star forming region (^{26}Al source)
M 22	9.89°	−7.55°	-	< 0.8	Globular Cluster
Palomar 13	87.10°	−42.70°	-	< 7.0	Globular Cluster
ω Cen	309.10°	+14.97°	-	< 1.7	Globular Cluster
NGC 6397	338.16°	−11.96°	-	< 1.2	Globular Cluster
M 4	350.97°	+15.97°	-	< 1.1	Globular Cluster
Sgr dwarf	5.61°	−14.10°	8°	< 1.7	Dwarf Galaxy
M31	121.17°	−21.57°	3°	< 11.8	Galaxy
LMC	280.47°	−32.89°	10.8°	< 4.7	Irregular Galaxy
QSO B2251-179	46.20°	−61.33°	-	< 2.9	QSO
3C 273	289.95°	+64.36°	-	< 1.2	QSO
3C 279	305.10°	+57.06°	-	< 1.3	Blazar
Cen A	309.52°	+19.42°	-	< 1.7	Radio Galaxy
Coma cluster	58.08°	+87.96°	4°	< 2.0	Galaxy Cluster
Perseus cluster	150.58°	−13.26°	4°	< 4.5	Galaxy Cluster
Virgo cluster	281.63°	+75.18°	12°	< 2.5	Galaxy Cluster

Comparison with OSSE

Table 5. Comparison of SPI results with OSSE measurements. The bulge parameters l_0, b_0, Δl, and Δb of OSSE were taken from Kinzer et al. (2001).

Quantity	SPI	OSSE
l_0	$-0.6^\circ \pm 0.3^\circ$	$-0.25^\circ \pm 0.25^\circ$
b_0	$+0.1^\circ \pm 0.3^\circ$	$-0.3^\circ \pm 0.2^\circ$
Δl (FWHM)	$8.1^\circ \pm 0.9^\circ$	$6.3^\circ \pm 1.5^\circ$
Δb (FWHM)	$7.2^\circ \pm 0.9^\circ$	$4.9^\circ \pm 0.7^\circ$
Flux (10^{-3} ph cm^{-2}s^{-1})	$1.5 - 2.9$	$1 - 3$
B/D flux ratio	$1 - 3$	$0.2 - 3.3$

No PLE!

OSSE PLE cutaway view

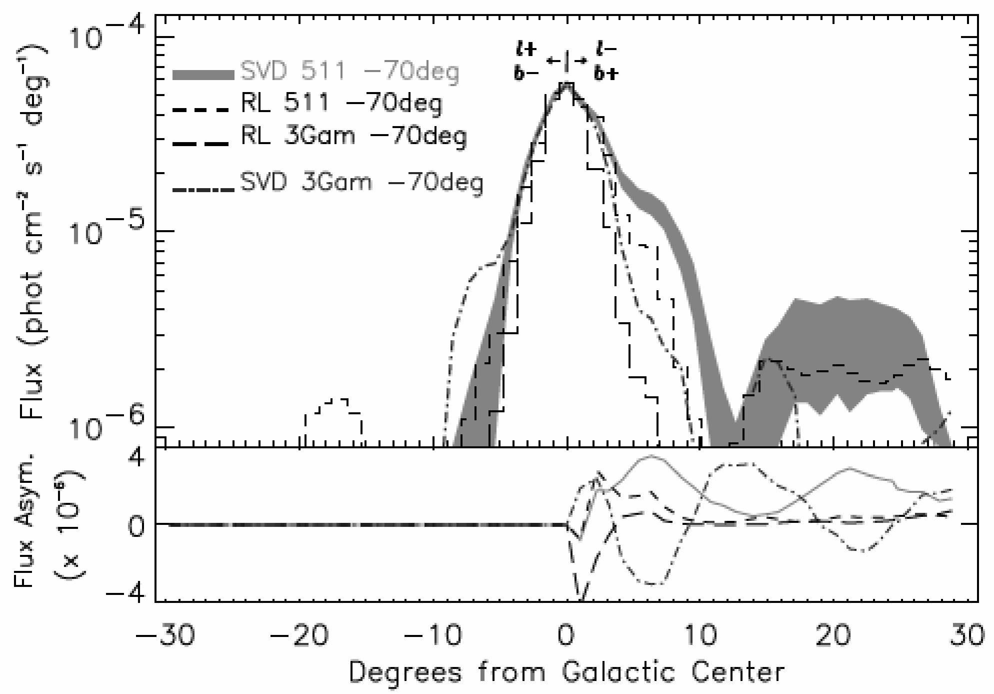


FIGURE 2. Cuts through the positive latitude enhancement taken at 70° relative to the negative-longitude galactic plane displayed on a logarithmic scale. Shown in the upper panel is a 1° wide cut through the RL and SVD maps of line and continuum annihilation radiation. The SVD -511 maps shows 1σ error bars. The lower panel shows the positive latitude portion of the cuts with the mirror negative latitude portion subtracted off.

Milne et al., AIP Conf. Proc. 587, 11 (2001)

Massive stars, core collapse supernovae, pulsars?

- WR stars and SN produce β^+ radioisotopes
- *Unlikely since the 511 keV emission shows bulge-like distribution, while massive star lies along the disk*
- (Faint disk emission may be explained via decay of ^{26}Al and ^{44}Ti)

Hypernovae

- Recent hypernova at the Galactic center
- *Unlikely since the 511 keV emission is bulge-like distribution (hypernovae, related to WR stars, should distribute along the disk)*

Cosmic-ray interactions

- N + p $\rightarrow \pi^+ \rightarrow e^+$ channel

- *Unlikely since GeV diffuse gamma-rays are distributed along the disk as shown by EGRET*

X-ray binaries

- $\gamma\gamma$ pair production in the luminous compact region around the compact object, or due to nuclear interactions which excite nuclei that β^+ decay
- Galactic B.H. and microquasars may eject positrons in jets
- HMXB: primarily found in disk
  LMXB: concentrated toward bulge

LMXB scenario

- 150 LMXBs:
  B/D=0.9, vertical scale height=410pc
- B/D is smaller than that of 511 keV emission, but positrons may escape into halo, since positrons are ejected into 10-100 less dense regions (since ISM scale height is ~100pc), thus substantial diffusion before annihilation
- *Individual LMXBs can be resolved?*

Classical novae

- Novae (thermonuclear runaways on white dwarfs in accreting binary systems):
  - B/D =3-4? (interstellar extinction!)
  - Produce β^+ decay isotopes in thermonuclear runaway of ^{13}N, ^{18}F, ^{22}Na...
- *^{22}Na requires 1600 novae/yr (obs.35$\pm$11/yr)*
- *^{13}N requires 26/yr but $\tau_{1/2}$=14min!*
  - *May rise transient annihilation signature*

Thermonuclear supernovae

- Supernova Type Ia:
  - Produce β^+ isotope, ^{56}Co (τ=111day)
  - 0.6M_{solar} ^{56}Co provide $2.5\times10^{54} e^+$
  - e^+ may not escape due to thick envelopes: escape fraction f~0.03? or 0?
  - 0.6 SN Ia/100yr required for f=0.03
  - *Estimated bulge SN Ia rate: 0.08/100yr?* B/D~3-4? if follows that of novae
  - *Search for 511 keV from nearby SN Ia!*

Light dark matter annihilation

- 1-100 MeV dark matter could emit positrons, but spatial distribution is poorly constrained.
- *If cuspy, inconsistent with 511 keV observation*

- 511 keV emission from nearby Sgr dwarf galaxy? (Hooper: $(1\text{-}7)\times 10^{-4}/\mathrm{cm}^2\mathrm{s}$)
  - *SPI limit $1.7\times 10^{-4}/\mathrm{cm}^2\mathrm{s}$*

Conclusion

- 511 keV emission is observed toward bulge (~50σ) and disk (~4 σ).
- No point sources up to 10^{-4}/cm^{2}s level.
- No PLE feature was observed.
- Bulge emission is spherically symmetric and is centered on the Galactic center with an extension of 8deg (FWHM).
- B/D ratio is 3-9.
- Emission may come from LMXB, SN Ia, or light dark matter annihilation.