Constraints on Galactic Positron Production

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(in collaboration with John Beacom)
~ $10^{50}$ positrons annihilating per year producing
0.511 MeV line flux of
~ $10^{-3}$ photons cm$^{-2}$ s$^{-1}$

no prominent disk component observed, unlike
gamma-ray maps tracing:

- cosmic-ray processes
  (COMPTEL 1-30 MeV continuum observations)
- nucleosynthesis (1.809 MeV line from $^{26}$Al decay)
Many Proposed Models/Studies for Positron Production

C. Boehm, D. Hooper, J. Silk, M. Casse, and J. Paul, MeV dark matter [1-100 MeV]
C. Picciotto and M. Pospelov, Unstable relics
M. Casse, B. Cordier, J. Paul and S. Schanne, Hypernovae/GRB
D. H. Oaknin and A. R. Zhitnitsky, Color superconducting dark matter
G. Bertone, A. Kusenko, S. Palomares-Ruiz, S. Pascoli and D. Semikoz, Gamma ray bursts
D. Hooper and L. T. Wang, Axino dark matter in the galactic bulge
P. D. Serpico and G. G. Raffelt, MeV-mass dark matter and primordial nucleosynthesis
W. Wang, C. S. J. Pun and K. S. Cheng, Pulsar winds
J. F. Beacom, N. F. Bell and G. Bertone, Gamma-ray constraint on Galactic positron ...
P. H. Frampton and T. W. Kephart, Primordial black holes
F. Ferrer and T. Vachaspati, Superconducting cosmic strings
S. Kasuya and F. Takahashi, Q balls
M. Kawasaki and T. Yanagida, Moduli decay
K. Ahn and E. Komatsu, MeV Dark matter
P. A. Milne, J. D. Kurfess, R. L. Kinzer and M. D. Leising, SNe and Positron Annihilation
N. Prantzos, On the intensity and spatial morphology of the 511 keV emission

...among many others....

yielding positrons of energies from few MeVs to the order of GeVs ....
0.511 MeV Line Formation

for each annihilated positron:

\[ 2 \left(1 - \frac{3}{4} f\right) \rightarrow 2\gamma \text{ annihilation line} \]
\[ 3 \left(\frac{3}{4} f\right) \rightarrow 3\gamma \text{ continuum} \]

\[ f = 0.967 \pm 0.022 \]
\[ \Phi_{0.511} = (1.07 \pm 0.03) \times 10^{-3} \text{ cm}^{-2} \text{ s}^{-1} \]

Guessoum Ramaty, 1991
it has been suggested that INTEGRAL data may favor either:

a single-phase weakly-ionized warm medium [Churazov et al, astro-ph/0411351]

a multi-phase medium dominated by warm neutral and warm ionized phases [Jean et al, astro-ph/0509298]

energy loss in neutral hydrogen:

\[
\left| \frac{dE}{dx} \right| \approx \frac{7.6 \times 10^{-26}}{\beta^2} \left( \frac{n_H}{0.1 \text{ cm}^{-3}} \right) (\ln \gamma + 6.6) \frac{\text{MeV}}{\text{cm}}
\]

positrons injected with energies 1-10 MeV may traverse distances of several Mpcs but can not diffuse more than few pcs from their origins due to magnetic fields of \( \mu \text{G} \) (typical of the region)
Inflight Annihilations and Positron Survival Probability

as noted by Heitler in
Quantum Theory of Radiation:

“up to 20% of ultrarelativistic positrons may annihilate inflight”

\[
\frac{dN(E)}{N(E)} = n_H \sigma(E) \, dx = n_H \sigma(E) \frac{dE}{|dE/dx|}
\]

\[
P_{E_0 \to E} = \frac{N(E)}{N(E_0)} = \exp \left( -n_H \int_E^{E_0} \sigma(E') \frac{dE'}{|dE'/dx|} \right)
\]

1.4%, 5.5%, 11% of positrons injected with energies 1, 3, 10 MeV are annihilated in flight until they lose most of their energy

\[
\frac{\Phi_{IA}}{\Phi_{0.511}} = \frac{2 (1 - P)}{2 (1 - 3f/4) P} = \frac{1}{1 - 3f/4} \frac{1 - P}{P}
\]
the differential cross section is sharply peaked at the endpoints of the $k$ range

as injected positrons lose energy, the low-energy peak remains below 0.511 MeV, where gamma rays are accumulated, while the high-energy peak moves slowly down to 0.511 MeV, producing a long tail

\[ \frac{d\sigma}{dk} = \frac{\pi r_e^2}{\gamma^2 \beta^2} \left( \frac{-(3 + \gamma)/(1 + \gamma) + (3 + \gamma)/k - 1/k^2}{[1 - k/(1 + \gamma)]^2} - 2 \right) \]

Svensson, 1982
Inflight Annihilation Spectrum Normalized 0.511 MeV Line Flux

\[ \frac{d\Phi_{IA}}{dk} = \frac{\Phi_{0.511}}{1 - 3f/4} \frac{n_H}{2P} \int_{E_0}^E P_{E_0 \to E} \frac{d\sigma}{dk} \frac{dE}{|dE/dx|} \]

inflight annihilation gamma ray spectrum

internal bremsstrahlung gamma ray spectrum

for positrons injected with 1, 3, 10 MeV

Beacom & Yuksel, to appear soon
the morphology of the angular distribution is well fit by a two-dimensional Gaussian of ~8° at FWHM

then the peak flux is ~0.048 photons cm⁻² s⁻¹ sr⁻¹

with 24% (80%) of the photons coming from a cone of half-angle ~2.5° (~6°) and the corresponding average fluxes are 0.042 (0.025) photons cm⁻² s⁻¹ sr⁻¹

Knodlseder et al, astro-ph/050626
for the diffuse flux, we adopted a power law that reproduces the COMPTEL measurements:

- $0.0096 \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ between 1-3 MeV
- $0.0043 \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ between 3-10 MeV

in the Galactic disk region ($330 < l < 30$, $|b| < 5$)

and also agrees reasonably well with the diffuse flux determination below 1 MeV from the INTEGRAL data alone:

$$\frac{d\Phi}{dE} = (E/0.09 \text{ MeV})^{-1.8} \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{MeV}^{-1}$$
about 24\% of 0.511 MeV positrons are coming from a cone of half-angle \(\sim 2.5^\circ\) at the galactic center for positrons injected with energies over 3 MeV, the excess radiation from inflight annihilations would significantly exceed the diffuse gamma-ray flux in the same region.

no such excess is seen in the COMPTEL sky maps for 1-3 MeV and 3-10 MeV energy bins
Conclusions

The intense 0.511 MeV gamma-ray line emission from the Galactic Center observed by INTEGRAL requires a large annihilation rate of nonrelativistic positrons.

If these positrons are injected at even mildly relativistic energies, higher-energy gamma rays will also be produced.

We calculate the gamma-ray spectra due to in-flight annihilations (and internal bremsstrahlung) and compare to the observed diffuse Galactic gamma-ray data.

Even in a simplified but conservative treatment, we find that the positron injection energies must be $< 3$ MeV.

This bound is far below the energy scales suggested in some recent models and it is therefore clearly very constraining.