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Sgr A* as Source of the Positrons Observed in the Galactic Center Region

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Abstract. We explore the possibility that a substantial fraction of the positrons observed to annihilate in the central region of our Galaxy come from the supermassive black hole Sgr A* that lies at the center. This idea was proposed by several authors, but the propagation of the emitted positrons into the bulge and beyond remained a serious problem for models of the origin of GC positrons.

We assume models of positron production with different energies. The propagation of positrons from their production site is followed in detail with Monte-Carlo simulations, taking into account the physical conditions of the propagation regions as well as various physical interactions. Using the known physics of positron annihilation in astrophysical environments, we calculate the properties of the annihilation emission (time evolution and spatial distribution) for the different models under consideration.

We present the results of these simulations and the conclusions/constraints that can be inferred from them.

Keywords. Positron Annihilation, Galactic Center, Gamma Ray Lines, Sgr A*

1. Introduction

Positron annihilation radiation has been observed for almost forty years now (see the full review by Prantzos *et al.*, 2010, and recently Siegert *et al.* 2016). Its flux and diffuse distribution, with a high concentration in the Galactic bulge, implies a rate of annihilation (and, in steady state, an equal rate of production) of positrons of $\sim 10^{43}$ per second. Determining the source(s) of positrons needed to explain this rate of annihilation as well as the observed spatial distribution has been a challenge, however. Indeed, positrons are known (Guessoum *et al.* 1991 and others) to live long ($\sim 10^5$ years in the ISM), and thus to travel far from their birth sites and die in regions where matter is more concentrated. Source distributions hence differ from annihilation maps.

The specific hypothesis we wish to explore here is whether positrons from the supermassive black hole (SMBH) Sgr A* could propagate in and fill the bulge. The idea of positrons being produced (in various ways) by the SMBH was proposed by several authors (Cheng *et al.*, 2006; Titarchuk & Chardonnet 2006; Totani 2006; Cheng *et al.*, 2007). Here we assume a collisional propagation of positrons and simulate their lives and deaths taking into account the physical conditions of the region (density, temperature, ionization, and magnetic field) and the main physical interactions until annihilation.

2. Models of Positron Production from Sgr A*

The models that have been proposed for the production and ejection of positrons from the SMBH can be categorized according to the physical process:

A) Pion production in collisions of high-energy protons with ambient protons, followed by pion decay to positrons via muons ($\mathrm{p}+\mathrm{p} \rightarrow \mathrm{p}+\mathrm{n}+\pi^{+}$, followed by $\pi^{+} \rightarrow \mu^{+} \rightarrow \mathrm{e}^{+}$). Several models have been proposed in this category: a) Fatuzzo *et al.* (2001), where p-p collisions producing π^0 to explain the EGRET spectrum of Sgr A East (Melia *et al.*, 1998) could also be invoked to produce π^+; b) Cheng *et al.* (2006, 2007), where the SMBH swallows a large star ($\sim 50M_{\odot}$) or a small one ($\sim 1M_{\odot}$) and produces flares of accelerated protons resulting in relativistic (~50 MeV) positrons on various timescales.

B) $\mathrm{e}^+\mathrm{e}^-$ pair production in photon-photon collisions in the vicinity of the SMBH ($\gamma + \gamma \rightarrow \mathrm{e}^+ + \mathrm{e}^-$). Different models fall into this category: a) Beloborodov (1999), noting that an $\mathrm{e}^+\mathrm{e}^-$ cloud must be created around a black hole's accretion disk, with a spectrum extending to MeV energies, applied it to Sgr A*, with its low compactness ratio (very low bolometric luminosity ($\sim 10^{36}$ erg/s) relative to its mass and size), to obtain a semi-relativistic ($v \sim c/2$) outflow of pairs with the needed rate ($\sim 10^{43}\mathrm{e}^+$/s). b) Titarchuk & Chardonnet (2006) postulated the existence of Small-Mass Black Holes (SmMBHs) of masses $\sim 10^{17}$ g in the central Galactic region, emitting blackbody-like radiation of $\sim$ 10 MeV temperature which collides with X-rays from Sgr A* to produce $\mathrm{e}^+\mathrm{e}^-$ pairs. c) Totani (2006) considered a radiatively inefficient accretion flow (RIAF) model for the SMBH's accretion disk; he assumed that the accretion rate and luminosity were higher than the present values by a factor of $10^3 - 10^4$, the rate dropping to its present level about 300 years ago when the expanding shell from the Sgr A East SN remnant collided with the accretion disk, in effect "breaking the engine"; non-relativistic pair production is then estimated to reach the required levels ($10^{43}\mathrm{e}^+$/s) and to stay in the bulge.

C) Dark matter annihilation ($\mathrm{dm} + \bar{\mathrm{dm}} \rightarrow \mathrm{e}^+ + \mathrm{e}^-$) or de-excitation ($\mathrm{dm}^* \rightarrow \mathrm{dm} + \mathrm{e}^+ + \mathrm{e}^-$). This applies to low-mass ($\sim$ MeV) particles, which works best to avoid violating $>$ 511 keV continuum observations. High-mass (GeV – TeV) particles could emit MeV positrons when transitioning from excited to ground states. This class of scenarios, however, suffers from highly uncertain density profiles of dark-matter candidates as well as from the non-detection of signal from satellite or nearby galaxies.

D) Other mechanisms. For example, Markoff & Falcke (2003) proposed a shock-acceleration of protons in jets during flares of the SMBH, assuming the SMBH does indeed have jets, at least during its flares.

3. Our Propagation Model

Our propagation model is the same as that presented in Alexis *et al.* (2014). It relies on Monte-Carlo simulations to compute the positions of positrons in our Galaxy as functions of time, taking into account their collisions (Coulomb, ionization, excitation, bremsstrahlung, synchrotron, and inverse Compton) as well as their annihilation with the interstellar matter. The propagation of positrons is followed assuming collisional transport, which is the most likely propagation mode for MeV positrons (Jean *et al.* 2009). In this mode, positrons spiral along magnetic field lines and their pitch angles are modified by collisions. Here we extend this mode to GeV positrons since, up to this energy, their Larmor radii are much smaller than the typical scales of magnetic turbulence.

Table 1 gives the parameter values describing the physical conditions of the Sgr A* region through which positrons propagate – and many annihilate. We adopt a detailed

Table 1. GC regions considered in the model and their physical conditions

Region	**Density and Size**	**Temperature**	**Ionization**	**Magnetic Field**
Central Cavity	varies ~ 1.2 pc radius	Cold & Warm	Partial	$\sim 0.1 - 1$ mG
CND Torus	$\sim 10^{4-5}$ cm^{-3} $1.2 - 3$ pc	~ 100 K	Neutral	~ 1 mG
Sgr A East	~ 6 cm^{-3} $(4 \times 4 \times 3)$ pc^3	$\sim 10^7$ K	Ionized	~ 0.1 mG
GMCs	$\sim 10^4$ cm^{-3}	~ 60 K	Neutral	~ 1 mG
Ionized Halo	$\sim 20 - 200$ cm^{-3} ~ 9 pc	$\sim 10^4$ K	90% Ionized	~ 0.1 mG

structure of the matter in this region and a simple topology of the magnetic field. The magnetic field is the sum of two components: (a) a large-scale regular field (horizontal with spiral arms in the disk, X-shaped in the halo, and vertical in the Sgr A* region) and (b) a small-scale turbulent field with maximum scale roughly the size of the local interstallar phase (molecular, cold, warm, or hot).

4. Results

Figure 1 shows the fractions of positrons (a) escaping the innermost region of radius 9 pc, (b) escaping the inner bulge (radius 200 pc) and annihilating inside the Galaxy, and (c) escaping the Galaxy, as functions of their initial energies. Most of the high-energy positrons (> 10 MeV) escape the Galaxy, while MeV positrons are the most efficient to fill and annihilate in the broad bulge.

Figure 2 shows the total positron energy in an outburst needed to produce the 511 keV flux measured today in the broad bulge by INTEGRAL/SPI (5×10^{-4} ph/s/cm^2) as a function of the outburst time, for various initial energies. The curves satisfy the requirement that the flux in the narrow bulge ($\approx 2°$) may not exceed the observed limit (1.5×10^{-4} ph/s/cm^2). We note that for initial positron energies < 10 MeV, the total energy needed is 10^{52-53} erg for outbursts of 10^{5-6} years. These total energies and outburst ages were suggested to explain the GeV excess observed with Fermi/LAT (Petrovic *et al.* 2014; Carlson & Profumo 2014; Cholis *et al.* 2015), although the source could be broader than Sgr A*. An outburst with higher initial positron energies could also explain the annihilation emission in the bulge, but it would require a larger total energy released at a later date.

5. Conclusions

Our model shows that an outburst of 10^{52-53} erg of MeV positrons from Sgr A* 10^{5-6} years ago could explain the measured 511 keV line flux in the broad bulge. The energetics and age of this event suggest a possible link between the positron annihilation emission and the GeV excess observed with Fermi/LAT.

The problem of the sources of positrons in the Galaxy is yet to be solved. Sgr A* may help solve the puzzle, if it swallows stars or other objects frequently enough or if its past accretion rate was 10^{3-4} times higher than now. Other candidates cannot yet be ruled out: radioactivity from SNe, microquasars, light dark matter.

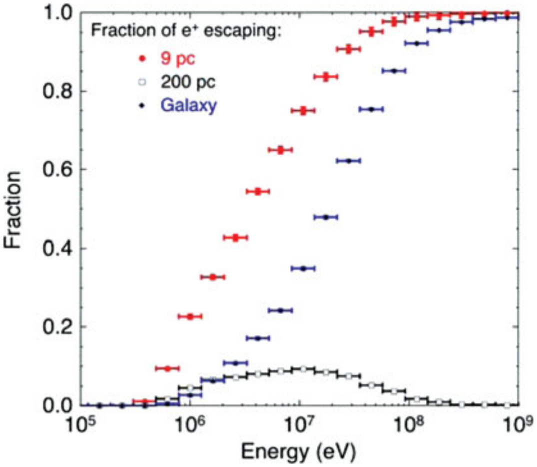

Figure 1. Fractions of e^+ escaping 3 Galactic regions, as functions of their initial energies.

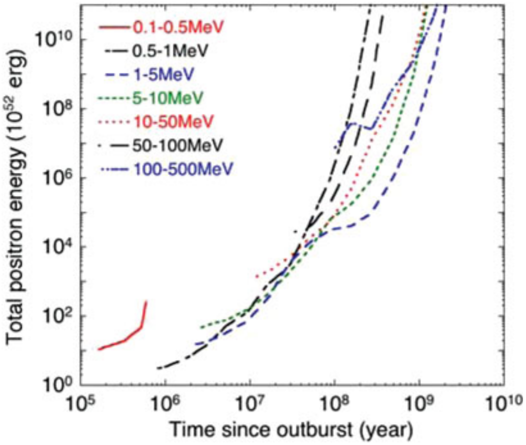

Figure 2. Total e^+ energy in an outburst needed to produce the 511 keV flux measured today in the broad bulge by INTEGRAL/SPI (see text).

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