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Restrictions on the injection energy of positrons annihilating near the Galactic center

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One of the interesting and still unsolved problems is the origin of 511 keV annihilation emission from the Galactic Bulge. One of the criterion, which may discriminate between different mechanisms of positron production there, is the positron energy injection. Beacom and Yüksel (2006) suggested a method to estimate this energy from the ratio of the 511 keV line to the MeV in-flight annihilation fluxes. From the COMPTEL data they derived that the maximum injection energy of positron should be about several MeV that cuts down significantly a class of models of positron origin in the GC. However, observations show that the strength of magnetic field in the GC is much higher than in other parts of the Galaxy. We show that if positrons injection in the GC is non-stationary and the magnetic field strength is higher than 0.5 mG both radio and gamma-ray restrictions permit their energy to be higher than hundreds of MeV.

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1. Introduction

The origin and properties of the source of positrons annihilating in the Galactic Center is still a mystery. The annihilation emission is observed as an extended diffuse emission from $5^\circ - 8^\circ$ radius region with the flux $\sim 8 \times 10^{-4}$ ph cm^{-2}s^{-1} that requires the rate of positron production there $\sim 10^{43}$ s^{-1} [12, 6, 11]. As follows from the Integral data [6] the energy of annihilating positrons does not exceed 1 eV. On the other hand, all potential sources of positrons in the Galaxy like SN stars [12], massive stars generating the radioactive ^{26}Al [19], secondary positrons from p-p collisions [4], lepton jets of AGNs [20], dark matter annihilation [3, 22], microquasars and X-ray binaries [26, 1] etc. generate positrons with energies ≥ 1 MeV. This means that positrons should effectively lose their energy before annihilation and thus generate emission in other than 511 keV energy ranges. Therefore, the injection energy of positrons is an essential parameter for modeling annihilation processes, and it can be in principle discriminated from observations.

High energy positrons annihilate "in-flight", thus producing continuum emission in the range $E > 511$ keV. A prominent 511 keV line emission is generated by these positrons when their energy is decreased to the thermal one due to energy losses. Therefore, one can expect that the continuum and line emission are proportional to each other.

In our recent paper [5] we derived variations of the injection energy of positrons as a function of the magnetic field strength. Below we analyse the effect of non-stationary injection of positrons.

2. Medium properties in the central region of the Galaxy

The inner bulge (200-300 pc) contains $(7-9) \times 10^7$ $M_\odot$ of hydrogen gas. Most of the molecular gas is trapped in very compact clouds of the mass $10^4 - 10^6 M_\odot$, the average densities $\geq 10^4$cm^{-3}.

This molecular gas occupies a rather small part of the central region, most of which is filled with a very hot gas. Recent SUZAKU measurements of the 6.9/6.7 keV iron line ratio [13] were naturally explained by a thermal emission of the 6.5 keV-temperature plasma. The plasma density was estimated in limits $0.1 - 0.2$ cm^{-3}.

One should note that there is no consensus on the magnetic field strength in the GC. Estimation ranges from about or smaller than hundred μG [23, 17, 10], up to several mG ([18, 24], see in this respect the review [7]). Radio observations of the central regions show that the structure of strong magnetic fields is nonuniform and it concentrates in filaments which extends up to 200 pc from the GC. The region containing mG magnetic field is estimated by the angular size $1.5^\circ \times 0.5^\circ$ [15, 25, 14]. In these magnetic fields synchrotron losses are essential even for positrons with energies 3-30 MeV.

Here we assume that positrons interact with this magnetic field which fills the central 100 pc sphere around the GC.

We shall show that the injection energy of positrons can be much higher than 1 MeV because of synchrotron losses in the Galactic center that extends significantly the class of models explaining the origin of annihilation emission from the bulge.

If it is not specified we accepted below that the central 100 pc radius region is filled with strong magnetic field and the gas density in the central region ($r \leq 500$ pc) is ≥ 0.2 cm^{-3}. The rate of ionization losses depends on the medium ionization degree. Therefore, we consider two cases of neutral and fully ionized medium.

3. Non-stationary model

We assume that the source of positrons was active in the past but ceased to exist at $t = 0$. The evolution of the total number of positrons with the energy E under these conditions can be described by the following equation

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial E}\left(\frac{dE}{dt}N\right) = Q(E)\theta(-t), \tag{3.1}$$

where dE/dt is the rate of positrons energy losses, $\theta(t)$ is Heaviside function and Q(E) is the injection spectrum of positrons.

The general solution of Eq. (3.1) can be expressed as

$$N(E,t) = \frac{1}{|dE/dt|}\int\limits_{-\infty}^{0} dt_0 \int dE_0 Q(E_0)\delta\left(\tau(E_0,E) - t - t_0\right), \tag{3.2}$$

where

$$\tau = \int\limits_{E_0}^{E} \frac{dE}{dE/dt}. \tag{3.3}$$

where E_0 is the injection energy of positrons.

The energy losses is a complicated function of energy since at high energies positrons loose their energy by synchrotron emission and at low energy by Coulomb interaction with background electrons. The synchrotron losses are described by the equation:

$$\frac{dE}{dt} = -\frac{2}{3}\frac{e^4H^2}{c^3m^2}\left(\frac{E}{mc^2}\right)^2 \tag{3.4}$$

The rate of Coulomb losses is [9, 8]

$$\frac{dE}{dt} = -\frac{2\pi e^4 n}{mc\beta(E)}\ln\Lambda \tag{3.5}$$

where $\beta(E) = v/c$ and $\log\Lambda$ is Coulomb logarithm, which equals

$$\log\Lambda \sim \log\left[(\gamma-1)(\gamma^2-1)\right] + 20.5\ , \tag{3.6}$$

for a neutral medium and

$$\log\Lambda \sim \log\left[\gamma/n\right] + 73.6\ . \tag{3.7}$$

in a fully ionized plasma. Here $\gamma = \frac{E}{mc^2} + 1$.

With this solution (3.1) we can calculate the fluxes of gamma-ray and radio emission from the GC expected at the present time t which in the model is the time passed from the moment of positron injection. The equations used for calculations of the emission are presented in [5]).

We assume that the central source injects a monoenergetic spectrum of positrons with the energy E_0. For a given set of E_0, the time t and the magnetic field strength H we calculate the total fluxes of radio emission at the frequency 330 MHz, the in-flight annihilation emission in the COMPTEL energy range from 1 to 30 MeV, and the 511 keV annihilation emission from the GC. As it was shown in [5]) the model estimations should correspond to the observed values presented in Table 1. For the COMPTEL energy range the in-flight fluxes should not exceed the COMPTEL 2σ level.

Table 1: Constraints of the model

Energy range	Observed flux
$\Phi_\nu(\nu = 330$ MHz) $1.5^\circ \times 0.5^\circ$ region	1 kJy
F_{1-3} MeV	$< 2 \cdot 10^{-4}$ ph cm^{-2}s^{-1}
F_{3-10} MeV	$< 9 \cdot 10^{-5}$ ph cm^{-2}s^{-1}
F_{10-30} MeV	$< 3 \cdot 10^{-5}$ ph cm^{-2}s^{-1}
I_{511} keV FWHM =6°	$8 \cdot 10^{-4}$ ph cm^{-2}s^{-1}

In Fig. 1 we presented permitted values of the injection energy E_0 as a function of the time t passed from the the moment of positron injection for different values of the magnetic strength H in the GC. One can see that for the magnetic field strength above 1 mG the injection energy is permitted to be higher than 100 MeV if the time t is about 10^5 years. Then e.g. the model of secondary positrons suggested by [4] is acceptable because in this model the injection energy of positrons is $E_0 > 30$ MeV and the average time between moments of positron injection is just about 10^5 years. In principle the value of magnetic field strength can be as small as 100 μG if the time $t > 10^7$ years. However, as follows from the estimates obtained by [4] the initial energy release in positrons in this case should be much higher than 10^{52} erg that cannot be even supplied by processes of star accretion onto the central black hole.

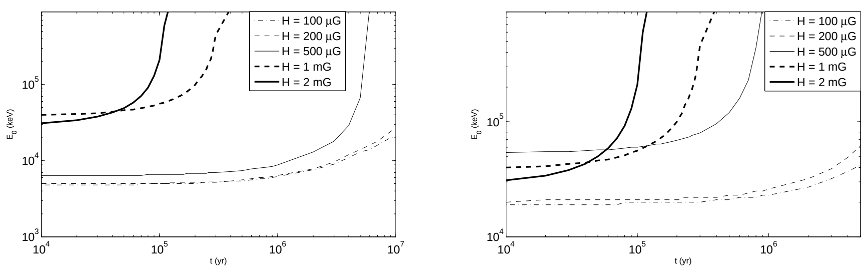

Figure 1: Dependence of maximum allowed injection energy on the time passed since positrons source ceased to exist for different values of magnetic field. The left figure corresponds to neutral medium while the right figure corresponds to ionized medium.

4. Discussion

The main constraints of our model are the size of positrons source and the time passed from the injection event. As we already shown in [5] the characteristic size of the source cannot exceed the radius of region with strong magnetic field. In that aspect our modification does not affect the models with extended sources of positrons like models of dark-matter origin [3, 22] or models with positrons transport from other parts of Galaxy [19].

Given the localization of the source the possible candidate for the origin modified by our model is the non-stationary process on central black hole occured more than 10^5 years ago. The possibility of such process is supported by the fact that about 300 years ago the central black hole may be much brighter than at the present moment [16, 21].

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