

Origin of nonthermal emission from the Fermi bubbles and mechanisms of particle acceleration there

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Introduction. The discovery of the two giant γ -ray lobes (Fermi bubbles) in the Galactic center (see Dobler *et al.* 2010 and Su *et al.* 2010) was one of the most impressive events of the last few years in astrophysics. However, some indications on giant structures in the Galactic center (GC) were observed several years before by *WMAP* in the radio frequency range between 23 and 33 MHz (Finkbeiner 2004), and by *ROSAT* in hard X-rays (Bland-Hawthorn & Cohen 2003). Recent observations performed by the Planck Collaboration (Ade *et al.* 2012) found also lobes in the microwave range which spatially coincided the Fermi bubbles that indicated on the common origin of these phenomena.

Parameters of emission from the Fermi bubbles have several remarkable distinction:

(a) The structures are symmetrically elongated in the direction perpendicular to the Galactic plane;

(b) Spectra from the nonthermal emission from the bubbles are harder than anywhere in the Galaxy;

(c) The spatial distribution of emission in the bubbles shows sharp edges of the bubbles;

(d) The surface emissivity is almost uniform inside the bubbles although findings of Hooper & Slatyer (2013) might indicate on features of the γ -ray spectrum at latitudes $b \leq 20^\circ$ which they interpreted as a contribution from the dark matter annihilation nearby the GC.

The origin of the bubbles is actively discussed in the literature. Thus, Crocker & Aharonian (2011) and Zubovas & Nayakshin (2012) suggested the hadronic origin of γ -ray emission from the bubbles, when γ -ray photons are produced by collisions of relativistic protons with that of the background gas. Alternatively, these γ -rays can be produced by the inverse Compton scattering of relativistic electrons on background photons (leptonic model) and the same electrons generate radio and microwave emission from the bubbles via synchrotron (see e.g. Su *et al.* 2010). There may be several sources (processes) which generate electrons in the bubbles:

- In-situ stochastic acceleration by MHD-turbulence nearby the bubble surface (Mertsch & Sarkar 2011);

- Acceleration by shocks which result from periodical star accretion onto the central black hole (Cheng *et al.* 2011);

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• Acceleration within jets near the GC about $\sim 10^6$ yr ago, and subsequent electron transfer into the bubble by convective flows (Guo *et al.* 2012 and Yang *et al.* 2013).

Below we discuss some of these models.

Stochastic acceleration from the background plasma. In order to reproduce the spatial distribution of γ -ray emissivity in the bubble Mertsch & Sarkar (2011) assumed arbitrarily that: a) the acceleration is nonuniformly distributed inside the bubbles and its efficiency increases near the shock which excited the MHD-turbulence inside the bubble; b) the maximum energy of electrons is a function of the distance to the shock.

There are no other evident sources for electrons accelerated in the halo except electrons from the background plasma and electrons injected by supernova remnants (SNRs) or jets. Estimates of acceleration efficiency in the case of stochastic (Fermi) acceleration from the background plasma is not trivial. As Wolfe & Melia (2006) and Petrosian & East (2008) showed, the energy supplied by sources of stochastic acceleration is quickly dumped into the thermal plasma because of ionization/Coulomb energy losses of accelerated particles. As a result this acceleration is accompanied by plasma overheating while a tail of nonthermal particles is not formed, i.e. the effect of stochastic acceleration is negligible.

However, latter Chernyshov *et al.* (2012) concluded that the efficiency of stochastic acceleration depended strongly on parameters of acceleration and prominent tails of nonthermal particles can be generated by the acceleration although the conclusions of Wolfe & Melia (2006) and Petrosian & East (2008) are correct for some conditions.

To define whether the stochastic mechanism is able to produce enough accelerated electrons needed for the observed flux of γ -rays we take the following parameters of the background plasma in the bubbles: the density $n = 10^{-2} \text{ cm}^{-3}$ and the temperature $T = 2 \text{ keV}$ (see Su *et al.* 2010).

The kinetic equation for the distribution function electrons, $f(p, t)$, when processes of spatial propagation are neglected, has the form

$$\frac{\partial f}{\partial t} + \frac{1}{p^2} \frac{\partial}{\partial p} p^2 \left[\left(\frac{dp}{dt} \right)_C f - \{D_C + D_F(p)\} \frac{\partial f}{\partial p} \right] = 0, \quad (0.1)$$

$(dp/dt)_C$ and $D_C(p)$ describe particle energy losses and diffusion in the momentum space due to Coulomb collisions. The stochastic (Fermi) acceleration is described as diffusion in the momentum space with the coefficient $D_F(p)$, which we take in the form: $D_F(p) = \alpha p^\zeta \theta(p - p_0)$ where α , ζ and p_0 are arbitrary parameters.

Parameters of this model can be restricted from the three conditions:

(a) The energy of electrons emitting γ -rays by inverse Compton is restricted by the value $\sim 10^{12} \text{ eV}$ (Su *et al.* 2010 and Cheng *et al.* 2011);

(b) The total γ -ray flux at energies $E > 1 \text{ GeV}$ is $F_\gamma \simeq 4 \times 10^{37} \text{ erg s}^{-1}$ that restricts the number of accelerated electrons (Su *et al.* 2010);

(c) Mechanism of particle acceleration should effectively generate nonthermal particles i.e. no plasma overheating (Chernyshov *et al.* 2012).

From the results of numerical calculations shown in Figure 1 we conclude that the stochastic acceleration from background plasma may provide the density and the spectrum of accelerated electrons needed for the observed γ -ray and radio emission from the bubbles if the parameters of the model are: $\zeta = 2.2$, $\alpha = 3.2 \times 10^{-15} \text{ s}^{-1}$, $p_0 = (0.2 - 0.5)mc$. The required power supplied by sources of acceleration is about $10^{38} \text{ erg s}^{-1}$ that does not exceed the upper limit of the rate of energy release expected in the GC which is in the range from 10^{39} (Crocker & Aharonian 2011) to $10^{41} \text{ erg s}^{-1}$ (Cheng *et al.* 2011).

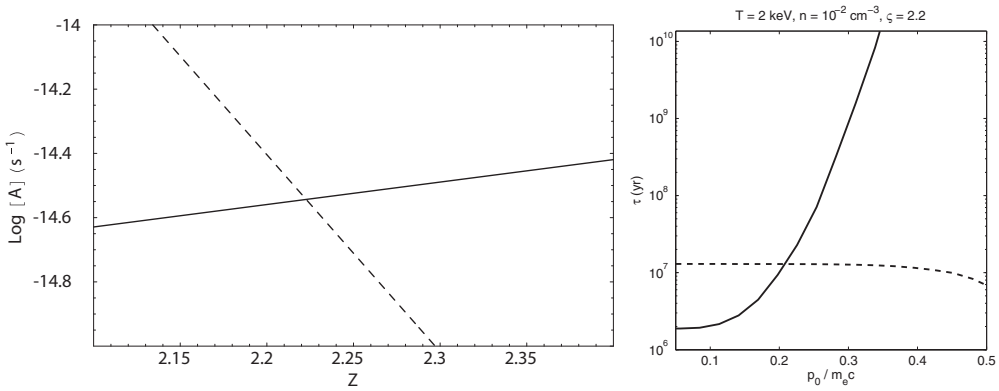


Figure 1. Left panel: The functions of $\alpha(\zeta)$ as derived from the conditions: a) - dashed dotted line; b) - solid line. **Right panel:** The timescales of temperature variations (solid line) and acceleration (dashed line) for different values of p_0 (condition c).

Stochastic re-acceleration of relativistic electrons emitted by SNRs in the Galactic Disk. In this case the kinetic equation has the form

$$-\nabla [D(r, z, p)\nabla f - u(r, z)f] + \frac{1}{p^2} \frac{\partial}{\partial p} p^2 \left[\left(\frac{dp}{dt} - \frac{\nabla \mathbf{u}}{3} p \right) f - \kappa(r, z, p) \frac{\partial f}{\partial p} \right] = Q(p, r)\delta(z), \tag{0.2}$$

where r is the galactocentric radius, z is the altitude above the Galactic plane, p is the momentum of electrons, u is the velocity of the Galactic wind, D and κ are the spatial and momentum (stochastic acceleration) diffusion coefficients, dp/dt describes the rate of electron energy losses, and Q describes the spatial distribution of CR sources in the Galactic plane ($z = 0$) and their injection spectrum.

As it follows from our hydrodynamic numerical simulations the process of re-acceleration of electrons is supposed to take place high above the Galactic plane in regions where the required MHD-turbulence is excited. Therefore because of the synchrotron and inverse Compton energy losses only relatively low energy electrons ejected by SNRs can reach this region. The thickness of re-acceleration region is defined from the intensity of the observed γ -ray and radio emission.

In the simplest case the number of electrons reaching the re-acceleration region can be calculated in the framework of the diffusion model of CR propagation (see Berezhinskii *et al.* 1990) when the convection terms are neglected ($u = 0$). For calculations we used the model parameters from Ackermann *et al.* (2012).

Our numerical calculations show that too many high energy electrons are produced in the re-acceleration region and, thus, the condition b) can not be satisfied in the model if the electron spectrum is formed by the acceleration processes only. Formally we can assume that processes of particle escape from the acceleration region are essential enough to make the spectrum steeper and thus to decrease the number of emitting electrons. Indeed, the momentum spectrum of accelerated particles is power-law, $f(p) \propto p^{-\delta}$, with the spectral index δ equaled

$$\delta = \frac{3}{2} + \sqrt{\frac{9}{4} + \frac{\tau_{acc}}{\tau_{esc}}}, \tag{0.3}$$

where the acceleration time $\tau_{acc} \approx \alpha^{-1}$ and escape time is $\tau_{esc} \approx \Delta r_b^2/4D$. Here Δr_b is the thickness of re-acceleration region and D is the spatial diffusion coefficient equaled $D(p) = 4v_a^2 p^2 / (6\kappa(p))$. Here v_a is the Alfvén velocity which is about 35 km s^{-1} in the Galactic halo (see Ackermann *et al.* 2012). The numerical calculations showed that the

model reproduces the γ -ray spectrum if $\alpha \sim 10^{-13} \text{ s}^{-1}$, $\Delta r_b \sim 10 \text{ pc}$, and $\delta \sim 4$. We notice, however, that the pure diffusion model of CR propagation has serious restrictions. In particular, the effect of convective transfer (Galactic wind) may be essential in the Galaxy as it follows from observations (see e.g. Carretti *et al.* 2013) as well as from theoretical treatments (Bloemen *et al.* 1993 and Breitschwerdt *et al.* 2002). The influence of the wind might decrease the density of SNR electrons in the halo significantly that possibly makes the effect of re-acceleration negligible.

Acceleration by shocks generated by processes of tidal disruption. We discussed this model in details in Cheng *et al.* (2011). In principle, this model describes quite reasonably the spectra of γ -ray and radio emission from the Fermi bubbles and it explains the shape of the bubbles because shocks propagate in the exponential atmosphere perpendicular to the Galactic plane (see Kompaneets 1960). However, serious simplifications were used for our calculations, e.g. we used the electron spectrum obtained in a stationary approximation although the situation of shock propagation in the halo is essentially non-stationary, we did not take into account shock evolution in the halo etc. However, we suppose that the shock model of the bubbles does not have serious objections up to now. The energy release from processes of star capture by the central black hole may release a huge energy up to 10^{54} erg . A part of this energy is transformed into a flux of hard X-ray emission. Very recently Swift detected to giant X-ray flares in normal galaxies whose luminosity was about $10^{45} - 10^{48} \text{ erg/s}$ (see e.g. Bloom *et al.* 2011). Such a huge flux of hard X-rays from Sgr A* may provide an observational effect in the Galactic molecular clouds seen at present in the form of "Compton echo" (see Cramphorn & Sunyaev 2002). Besides, some results of observations have been already interpreted as traces of past activity of Sgr A* with a very high energy release (see Bland-Hawthorn *et al.* 2013 and Nakashima *et al.* 2013) that is in favor of our model.

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