Fermi bubbles, their origin and possible connection to cosmic rays near the Earth

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Abstract. Discovery of two giant structures seen in gamma-rays and radio, located above and below the Galactic center, known as Fermi bubbles, can be considered as one of the most interesting phenomena observed by Fermi-LAT. Their position and total energy content suggest a very strong energy outburst happened in the Galactic center in the past. We point out some limitations of theoretical models of Fermi bubbles. We also discuss interconnection between Fermi bubbles and Galactic cosmic rays. In particular, we point out that gamma-ray emitting electrons in the bubbles are most likely originated from cosmic ray electrons. In addition we show that Fermi bubbles may be responsible for the formation of the spectrum of cosmic rays above the “knee”.

1. Introduction

Bipolar gamma-ray structures in our Galaxy correlated with the Galactic center also known as Fermi bubbles belong to the most remarkable discoveries made by Fermi-LAT. Initially discovered by two independent groups [23] and [39] and later confirmed by Fermi collaboration [3], Fermi bubbles remain as one of the most interesting astrophysical phenomena. They exhibit a very large size of order of 1 sr, making them the largest gamma-ray objects observed on the sky.

Fermi bubbles also are observed in other wavelengths. In particular observations in microwave band show a very good correlation of so-called ”WMAP haze” with gamma-ray emission [4, 25]. There are some indications on the hot plasma inside the Fermi bubbles observed by a ROSAT as a narrow envelope with very sharp edges [10]. This structure is explained as a fast wind with a velocity \( u_w \sim 10^8 \) cm/s driving a shock into the halo gas. However subsequent observations of Fermi bubbles edges by Suzaku did not find any evidences of a strong shock there [30].

Since Fermi bubbles are very faint structures it is very difficult to observe exactly the same phenomena in other galaxies. Recently there was a claim of presence of similar objects in the galaxy M31 [36], but it was not confirmed by the Fermi collaboration. However some much more powerful objects with similar properties and probably similar nature are observed in some galaxies with active nuclei. For example even more giant structures are clearly seen in the direction of Cen-A in GHz radio [24, 29], GeV [43] and TeV [7] gamma-ray ranges. Giant X-ray
and radio lobes (bubbles) were found also in the galaxies NGC 3801 [22], Mrk 6 [33] and Circinus Galaxy [34].

The nature of Fermi bubbles is being intensively discussed and a lot of phenomenological models were suggested (see review of [42] and references therein). With rather arbitrary parameters of the models it is possible to reproduce characteristics of emission from the bubbles. However, plausibility of these model is in many cases an open question.

In general, observations of powerful nonthermal emission the bubble from the bubbles indicate that they are source of CRs and may contribute into the total flux of CRs in the Galaxy. In this paper we estimate below this contribution into the total flux of CR electrons and protons.

2. Important properties of Fermi bubbles

Fermi bubbles have several peculiar properties that should be taken into account in theoretical models [3, 39].

- The surface brightness of the bubbles is uniform. Therefore their volume emissivity is non-uniform and edges of the bubbles should emit more gamma rays in comparison to the central part. Total gamma-ray flux is \( F_\gamma \approx 4 \times 10^{37} \text{ erg/s} \).
- Edges of the bubbles are sharp. Transition region between the bubble interior and exterior occupies less than 2° -3° and is very small in comparison to the size of the bubble of 60°.
- Spectrum of the gamma-ray emission is the same everywhere in the bubble. The spectral variations suggested by [27] and [45] was not confirmed by analysis of [3]. The spectral index of gamma-ray emission equals -2 in energy range between 1 GeV and 100 GeV. Below 1 GeV there is a cut-off or spectral hardening and above 100 GeV there is an indication on spectral softening or a possible high-energy cut-off.

Theoretical models of Fermi bubbles can be separated into two major groups. There are hadronic models, where gamma-ray emission generated by proton-proton collisions and leptonic models, where gamma rays are produced by inverse-Compton scattering of relativistic electrons on soft (background) Galactic photons. At present neither of them can be completely ruled out. Below we present a preliminary analysis of the bubble emission, which may give ideas how to differentiate between these models if more detailed analysis or better observational data are available.

The first indication may come from radio observations of the Fermi bubbles. Indeed observations of WMAP and subsequent observations by Planck showed that a micro wave flux came from the region of Fermi Bubbles with a power-law spectrum:

\[ \Phi_{FB}^{\nu} \propto \nu^{-\alpha}, \]  

where \( \alpha \) is the spectral index of emission which is between 0.5 and 0.63 at GHz frequency range. If the emission is synchrotron emission, then spectrum of the radio emitting electrons is close to a power-law,

\[ N_e \propto E_e^{-(2\alpha+1)}. \]  

Therefore the spectral index of radio emitting electrons should be close to -2.

These observations make the hadronic model problematic. If the gamma-ray emission is produced entirely by proton-proton collisions, then the spectral index of relativistic protons equals -2. The spectrum of secondary electrons produced by these protons has the spectral index -3 because of inverse-Compton and synchrotron losses, that is too steep to reproduce the observed radio emission. To make radio emission consistent with observational data one need to assume that there is an additional component of primary electrons responsible for the radio emission.
This model was analyzed in [18] and it was shown that under ideal background parameters hadronic emission may be responsible only less than 80% of the total gamma-ray flux. And at least 20% of the flux should be produced by primary electrons.

The observed spectral features at $E_\gamma < 1$ GeV and at $E_\gamma > 100$ GeV of the gamma-ray spectrum provide also restrictions for bubbles models. The feature at 1 GeV in the case of hadronic origin may be related to a threshold of the neutral pion production in the proton-proton reaction. In leptonic models explanation of this hardening is quite different. It is usually assumed that spectrum of electrons has a spectral index of -2 and a cut-off at several hundred GeV. Therefore spectrum of leptonic gamma-ray emission produced by inverse-Compton scattering of monoenergetic soft photons should be rather hard with spectral index of -1.5. On the other hand, above the Galactic plane we have at least 3 types of soft photons: relic, infra-red and optical. Their combination mimics a power-law spectrum with the index of -2. At low enough energies however only scattering on relic photons dominates that provides the spectrum hardening.

Taking this into account one can predict that spectrum of leptonic emission will most likely continue with index of -1.5 to low energies. For hadronic emission the situation is slightly different. Due to emission of secondary electrons with soft spectrum the overall spectrum gamma-ray emission should experience an upturn at low energies (see, e.g. [41]). The absence of the emission from secondary electrons at low energies can be a strong argument in favor of leptonic model, however the opposite is not necessary true. To test this scenario observation below 100 MeV are necessary.

In leptonic models high energy cut-off should be at fixed position since fine adjustment is required to mimic the spectral index of -2. Hadronic models on the other hand are more relaxed. Current observations by Fermi-LAT [3] and HAWC [1] do not provide sufficient limitations for leptonic models, but in the future can potentially help to differentiate the origin of Fermi bubbles [37].

In the next two sections we are going to briefly discuss some complications of both hadronic and leptonic models.

### 3. Restrictions on the hadronic wind model

Hadronic wind model suggested by [21] assumes that relativistic protons generated in star formation regions within the central 200 pc radius are carried into the Galactic halo by plasma outflow and somehow trapped there for the time of proton-proton collisions. The total energy release in the central region was estimated as $10^{40}$ erg/s which is significantly larger than total gamma-ray brightness of the Fermi bubbles.

The problem of the model is the necessity to confine protons stored inside the Fermi bubbles for a very long time of proton-proton collisions, $\tau_{pp} = (n_0 \sigma_{pp} c)^{-1} \approx 4 \times 10^{10}$ yrs where $n_0 \approx 10^{-3} \text{cm}^{-3}$ is the gas density in the Fermi bubbles [30] and cross-section of proton-proton collisions is $\sigma_{pp} \approx 3 \times 10^{-26} \text{cm}^2$. Then we should assume mirroring magnetic walls at the bubble edges [28].

The energy density of magnetic field there should exceed the energy density of CR protons in the bubbles. The latter can be estimated based on the surface brightness of the Fermi bubbles $I_\gamma \approx 5 \times 10^{-7}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ as

$$\epsilon_p = \frac{4 \pi I_\gamma}{2 \times 0.075 \sigma_{pp} n_0 c \times 2 L} \ln \left( \frac{E_{\text{max}}}{E_{\text{min}}} \right) \approx 18 \log_{10} \left( \frac{E_{\text{max}}}{E_{\text{min}}} \right) \text{eV cm}^{-3},$$

where $L \approx 1$ kpc is the characteristic size of the gamma-ray emitting region in the bubbles and 0.075 is an average fraction of the energy transferred from the proton to gamma-ray photon. $E_{\text{max}}$ and $E_{\text{min}}$ are maximum and minimum energy of protons.

To confine protons with energy density of 18 eV cm$^{-3}$ it is necessary for the magnetic field to be at least of order of 20 $\mu$G. This value is very high even in comparison to the magnetic field strength in the Galactic disk and can potentially create some problems for explanation of the
radio-emission [18]. The other problem is that observations of gamma-ray emission of molecular clouds give an estimate of CR energy density below 10 eV cm\(^{-3}\) [44].

Another problem may come from the fact that regular magnetic field cannot confine particles forever. Even in absence of turbulence there will be Hall diffusion or drift across the field lines with diffusion coefficient of order of \(D_b \approx r_L c/3\), where \(r_L\) is particle gyroradius. The flux of escaping protons can be estimated as \(j_{esc} = D_b \frac{\partial N_p}{\partial r} \approx D_b N_p \frac{\delta L}{r_L}\), where \(N_p\) is the density of the relativistic protons and \(\delta L \leq 0.3\) kpc is the characteristic size of the transitional region between the bubble and halo [3].

Therefore one can compare life time of the protons due to escape through the bubble walls with life time of proton-proton collisions:

\[
\frac{\tau_{pp}}{\tau_{esc}} \approx \frac{r_L}{3 \sigma_{pp} n_0 L \times \delta L} = 0.7 \times \left( \frac{B}{20 \mu G} \right)^{-1} \times \left( \frac{E}{1 \text{ TeV}} \right). \tag{4}
\]

It interesting to note that escape of relativistic protons starts at about 1 TeV, which corresponds to a high-energy turn-over in the gamma-ray spectrum.

The difficulties of confinement of protons can be resolved in hadronic jet model which does not assume stationary state and uses a single event to power the bubbles. However the total energy in this event should reach enormous value of \(W \approx F_{\gamma} t_{pp} \approx 10^{56}\) erg.

4. Acceleration of electrons inside the bubbles
The energy of relativistic electrons needed to produce 100 GeV gamma-ray emission is about or more than several hundred GeV. Lifetime of these electrons is quite short in comparison with that of protons (\(\tau_e \sim 3 \times 10^6\) yrs). Therefore, these electrons should be produce directly inside or nearby the emission region of the bubbles, i.e. nearby the bubble edges. Two different mechanism of electron acceleration were suggested. Thus, [16] assumed that these electrons were accelerate by a shock/shocks penetrating into the halo, which are produced by energy release in the GC due to a tidal disruption of a star on the central black hole. The spectrum of electrons accelerated by a shock is \(\propto E^{-2}\) as needed for the observed gamma-ray from the bubbles. This model with a set of free parameters (like the number of accelerated particles or the coefficient of spacial diffusion near the shock etc.) is able to reproduce the observed gamma-ray and microwave emission from the bubble. The maximum energy of accelerate electrons is derived from the equality condition between the time of shock acceleration and the time of energy losses [12]. Although a shock is not observed directly, there are some indication for supersonic fluxes of plasma there (see [26]).

Alternatively, electrons can be accelerated by a magnetic turbulence excited behind the shock as suggested by [31]. This type acceleration is similar to classical stochastic acceleration suggested by Fermi in 1954, which produce hard spectra (\(\propto E^{-1}\)). However, the arbitrary assumed spatial dependence of a cut-off in the spectrum makes the gamma-ray flux close to \(E^{-2}\) because of integration along the line of sight.

The number of accelerated particles depends on the process of efficiency of particle injection into the acceleration regime. The latter is usually omitted since correct description of the injection requires careful analysis of the spectrum of turbulence at very short wavelengths. However this information is crucial for determination of the magnitude of the accelerated particles spectrum. Also, the knowledge about particle injection is also important for understanding if stochastic acceleration is effective for generation of nonthermal spectra or the interaction between charged particles with turbulence results only in heating of the background plasma, i.e. no acceleration [20, 35].

Since Fermi bubbles are located in the Galactic halo it is necessary to take into account that injection of electrons for any type of acceleration can happen from two main sources of particles:
either from thermal plasma or from the cosmic ray electrons. The thermal plasma has much more seed electrons therefore potential magnitude of the spectrum can be very high. On the other hand, cosmic ray electrons have much higher energy therefore it is easier to accelerated them.

Therefore for low acceleration rate is most likely that injection from cosmic ray electrons will be higher than injection from thermal plasma. As acceleration rate increases, the thermal plasma contribution will increase and at some point it may overcome the contribution from cosmic rays. However for the parameters of Fermi bubbles acceleration rate is not enough for thermal plasma to dominate and the main sources of the seed electrons are CRs [19], despite this fact is usually ignored for the studies of acceleration of particles in Fermi bubbles.

The major advantage of using cosmic rays as seed particles for acceleration is the fact that injection happens in the energy range where acceleration totally dominates over losses. E.g. in the case of stochastic acceleration if we assume that turbulence have a power-law spectrum, a power-law tail of particles should be formed. The reacceleration process can be roughly described as a smooth attachment of a power-law tail to the background distribution function i.e. the reaccelerated spectrum looks like

\[
f_r(E) = f_0(E)\Theta(E_c - E) + f_0(E_c) \left(\frac{E}{E_c}\right)^{-\delta_1} \Theta(E - E_c),
\]  

(5)

where \(f_0(E)\) is the initial spectrum of particles before the reacceleration and \(E_c\) is determined from the continuity of the particle flow in the energy space. In most cases \(E_c\) can be estimated from the continuity of the derivative \(\frac{\partial f}{\partial E}\). In the case of Galactic CR electrons the spectrum \(f_0(E)\) have a sharp spectral break near 2.2 GeV so it is reasonable to assume that \(E_c \approx 2\) GeV.

The intensity of the inverse Compton emission can be estimated in the following way

\[
I_{IC} = \frac{\Delta x}{4\pi} \int_{E_{IC}^{(min)}}^{E_{IC}^{(max)}} f_r(E) \left(\frac{dE}{dt}\right)_{IC} dE,
\]  

(6)

where \(E_{IC}^{(min)}\) and \(E_{IC}^{(max)}\) is energy of the electrons corresponding to maximum and minimum energy of gamma-ray photons accordingly and \((dE/dt)_{IC}\) are inverse Compton energy losses. Using for simplicity non-relativistic approximation \((dE/dt)_{IC} = \beta_{IC} E^2\) and assuming that \(\delta < 3\) one can obtain that the thickness of the gamma-ray emitting region is

\[
\Delta x = I_{IC}^{-1} \frac{4\pi(3-\delta)}{\beta_{IC} f_0(E_c)} \left(\frac{E_{IC}^{(max)}}{E_c}\right)^{4-3} E_c^{-3}.
\]  

(7)

According to the one of the publicly available GALPROP simulations \(S_8Z_8R_{20}T_{int}C_2\) [2] the density of electrons at 2 GeV is \(f_0(E_c) = 8.7 \times 10^{-16}\) cm\(^{-3}\)MeV\(^{-1}\). The cut-off in the gamma-ray spectrum requires \(E_{IC}^{(max)} \approx 0.3\) TeV [39] and \(\delta = 2.1\) as it is required by radio observations [4]. Therefore the thickness of FERMI bubble walls is only \(\Delta x = 30\) pc. This value is much smaller than the value of 1-2 kpc required to reproduce the spatial shape of the bubble and also require an extremely small spatial diffusion coefficient to confine relativistic electrons in a thin shell. A finer \(\Delta x(\delta)\) relations based on the correct expressions for the gamma-ray and radio emission together with some restriction from observation data are presented in Fig. 1.

One can conclude that reacceleration process overproduces relativistic electrons. This effect does not depend on the nature of the reacceleration mechanism as long as it produces power-law spectrum of electrons. To avoid this problem it is necessary to introduce another kind of losses
which should be effective in GeV energy range. One of the possible solutions is introduction of adiabatic losses. Indeed if the plasma flow in the Galactic halo in the vicinity of Fermi bubbles is non-uniform particles start to lose energy with a rate

$$\frac{dE}{dt} = \frac{E}{3} \nabla \cdot \mathbf{u},$$

where $\mathbf{u}$ is the flow velocity. According to [11] the velocity of the Galactic wind can be described as linear function of the altitude $u(z) = 3v_0z$ and the gradient value $v_0$ can be as high $v_0 \approx 10^{-15} \text{s}^{-1}$. With this rate adiabatic losses become essential in GeV energy range and are able to significantly reduce the value of $f(E_0)$ in (7) and soften the restrictions on $\Delta x$ and $\delta$. As we showed in [19] this assumption indeed helps to reproduce observed spectrum of the gamma-ray and radio emission using reacceleration of the CR electrons.

Another way to avoid this problem is to take into account anisotropic diffusion of electrons and structure of the global magnetic field in the vicinity of Fermi bubbles [32]. Since diffusion of the particles across the magnetic field lines is much weaker than the diffusion along the field lines, injection of the CR electrons into the acceleration zone may be limited. Careful analysis of the acceleration may solve the problem of particle overproduction.

5. Influence of Fermi bubbles on the spectrum of cosmic rays near the Earth

Since size of the Fermi bubbles is huge, one can expect that Fermi bubbles should also affect the population of CRs near the Earth. The effect of reacceleration should appear as a "bump" in the spectrum of electrons at energies of about 10-100 GeV. Indeed, Fermi bubbles act as a source of electrons with spectral index close to -2, while Galactic sources should produce electrons with spectral index close to -2.4 [2]. Therefore combination of these two sources should produce characteristic features in the spectrum of CR electrons. This component may be related to the spectral hardening seen by AMS-02 [6] and CALET [5] in the spectrum of electrons. However since electrons are strongly affected by energy losses, a careful detailed analysis required to estimate the possible influence of Fermi bubbles on the spectrum of CR electrons near the Earth.

Even stronger effects are expected if we take into account reacceleration of Galactic protons and nuclei, which are almost unaffected by energy losses during their propagation in the Galaxy. The important point of the CR spectrum is sudden steepening around $3 \times 10^{15}$ eV which indicates
on the change of the acceleration or propagation mechanism. Smooth attachment of the spectra above and below this energy and sharpness of the transition indicates that we are dealing with sole spectrum rather than with sum of two distinct components. The review of different models suggested to explain this phenomenon can be found in the original paper [17].

In summary, it is generally agreed that supernova remnants (SNR) shocks can only accelerate particles to energies $E < 10^{15}$ eV. Acceleration beyond this energy by SNRs is problematic due to restriction on the maximum energy for a typical SNR of age $T$ expanding with velocity of $u_{sh}$

$$E_{\text{max}} \sim Z e \beta_{sh} B T u_{sh},$$

where $\beta_{sh} = u_{sh}/c$, $B$ is the magnetic field strength at the shock and the term $E = \beta_{sh} B$ in this case can be interpreted as an effective electric field.

However Fermi bubbles with age and size exceeding that of typical SNR by 3 orders of magnitude can easily accelerate particles to much higher energies. Using Eq. (9) one can estimate that the bubbles have a potential to form the spectrum of CR in between $3 \times 10^{15}$ eV and $10^{18}$ eV. We do not consider the possibility that Fermi bubbles can form a whole spectrum of CR both below and above $3 \times 10^{15}$ eV. The reason for this is that the total power needed for the luminosity of CRs in our Galaxy $L_{CR} \sim 10^{41}$ erg/s [8] and the average energy release toward the Fermi bubbles is also $10^{41}$ erg/s [16]. Thus our model can be described in the following way: SNR in the disk accelerate particles with power-law distribution up to energies of $3 \times 10^{15}$ eV and Fermi bubbles further re-accelerate this particles up to $10^{18}$ eV.

In our model for simplicity we assume that CRs only consist of protons. Despite actual spectrum of CRs is more complicated, we only want to use a toy model as a proof of concept. We note that since acceleration properties of nuclei depend only on their rigidity, application of the model to the multi-component spectrum of CRs is straightforward. However detailed information about the spectra of each CR specimen produced by SNRs is required.

In the model of Fermi bubbles origin we suggested that the activity responsible for the formation of the bubbles was due to stellar capture and tidal disruption by a central black hole [16, 17]. The average time between two successive captures in the Galaxy is between $10^4$ yrs and $10^5$ yrs [40]. Thus the activity is periodic and characteristic period between two event is shorter than the characteristic lifetime of the Fermi bubbles. Periodic energy releases in the Galactic center should form series of shocks propagating through the halo.

The problem of particle acceleration in conditions of supersonic turbulence (multi-shock structure) was extensively analyzed before. In series of papers by [14, 13, 15] as applied to acceleration processes in OB associations, which is quite similar to the structure of the Bubble, they introduce a nondimensional parameter characterizing acceleration regime as

$$\psi = \frac{l_{sh}}{l_D} = \frac{u_{sh}}{D} \sim \frac{u_{sh}}{c r L}.$$ (10)

The corresponding energy $E_1$ that separates different regimes can be estimated from the condition $\psi \sim 1$ or $l_D(E_1) \sim l_{sh}$ which for the conditions of the Fermi bubble is

$$E_1 = e B l_{sh} u/c = 10^{15} \left(\frac{B}{5 \, \mu G}\right) \left(\frac{l_{sh}}{30 \, \text{pc}}\right) \left(\frac{u}{10^8 \, \text{cm/s}}\right) \text{eV.}$$ (11)

In the case of $\psi \gg 1$ or $l_{sh} \gg l_D$ analyzed in [14, 13], there is a combined effect of a fast particle acceleration by a single shock, which generates the spectrum $E^{-2}$ and relatively slow transformation of this spectrum due to interaction with other shocks (stochastic Fermi acceleration) into a hard $E^{-1}$ spectrum in the intershock medium at relatively low energies. However it is unclear if such slow transformation can be completed within the life time of the shocks in the Bubble. Furthermore the hard $E^{-1}$ spectrum requires the power which significantly
exceeds $10^{41}$ erg/s which the bubbles can not supply. It is reasonable to assume that Fermi bubbles do not affect the spectrum of CR below $E_1$.

For $\psi \ll 1$ or $l_{sh} \ll l_D$ the acceleration regime changes to a pure stochastic acceleration by a supersonic turbulence. In the stationary case the equation for accelerated CRs can be presented in the form [14]

$$\frac{\partial}{\partial z}D(\rho)\frac{\partial f}{\partial z} + \frac{1}{\rho}\frac{\partial}{\partial \rho}D(\rho)\rho\frac{\partial f}{\partial \rho} + \frac{1}{p^2}\frac{\partial}{\partial p}\kappa(\rho)p\frac{\partial f}{\partial p} = 0$$  \hspace{1cm} (12)

where $\rho$ and $z$ are the cylindrical spatial coordinates, $p$ is the particle momentum, $D(\rho)$ is the spatial diffusion coefficient and $\kappa$ is the momentum diffusion coefficient.

We present the bubble region as a cylinder extending above and below the Galactic plane from $z = 0$ to $z = \pm H$ with a radius $\rho = \rho_B$. As the boundary conditions we put the density of particles $f$ equaled zero at the Galactic halo surface.

The diffusion coefficients inside and outside the bubble are supposed to be different

$$D(\rho) = D_B\theta(\rho_B - \rho) + D_G\theta(\rho - \rho_B)$$

$$\kappa = \kappa_B\theta(\rho_B - \rho)\Theta(E - E_1)$$  \hspace{1cm} (13)

where $D_B = Lc/3$ is the coefficient inside the bubble due to interactions with a supersonic turbulence and $D_G$ is the average diffusion coefficient in the Galaxy defined e.g. in [9]. The momentum diffusion coefficient is $k_B = p^2u^2/9D_D$ and we assume that there is little or no stochastic acceleration outside the bubble.

The momentum dependence of $f$ can be presented by a power-law function, $f(p) \propto p^{-\gamma}$, where $\gamma$ is determined by balance between acceleration inside the bubble and escape. From Eq.(12) it can be approximated as

$$\gamma \approx 3 + \sqrt{\frac{9}{4} + \frac{\pi^2D}{\rho_B^2\kappa}} = 3 + \sqrt{\frac{9}{4} + \frac{\pi^2D_B^2}{u^2\rho_B^2}}.$$  \hspace{1cm} (14)

Similarly to the reacceleration of the CR electrons one can expect that inside the bubbles spectra produced by SNRs and reaccelerations should be smoothly connected and described by Eq. (5) with corresponding choice of spectral indexes. However spectrum near the Earth should be distorted by propagation and escape from the Galaxy. Since sources of CR above the knee and below the knee are located in the different parts of the Galaxy, it is not obvious that smooth connection of the spectra will remain.

To test this idea, we work out a concrete numerical model. Essentially, we solve the stationary state CR transport equation (12) in our Galaxy with two Fermi Bubbles (one on each side of the Galactic plane). We modeled our Galactic halo as a cylinder of radius $\rho_G = 20$ kpc, and the top and bottom at $\pm 10$ kpc from the mid-plane. Each Fermi Bubble is also a cylinder of the same height $\pm 10$ kpc, but with a radius $\rho_B = 3$ kpc. The spatial diffusion coefficient are different inside and outside the bubble as described by Eq. (13).

Since we expect the average separation between shock in the Fermi bubbles to be of order of $100$ pc [17] we consider a constant spatial diffusion coefficient and adopt $D_B = 2.08 \times 10^{30}$ cm$^2$ s$^{-1}$. Outside the bubble, we take into account the energy (or momentum) dependence of the spatial diffusion coefficient and adopt $D_G = D_0(pc/4\text{GeV})^{0.6}$, $D_0 = 6.2 \times 10^{28}$ cm$^2$ s$^{-1}$ [2].

For Galactic SNRs adopt the distribution suggested by [38] and modified it with a Gaussian thickness profile. We adopt the idea that SNRs inject energetic particles in the form of a power law with a high-energy cutoff at $p_{\text{max}}c \approx 3 \times 10^{15}$ eV. Therefore the source function is

$$Q(\rho, z, p) = Q_0 \left(\frac{p}{p_{\text{max}}}\right)^{-\mu} \exp\left(-\frac{p}{p_{\text{max}}}\right) (\frac{\rho}{\rho_G})^{1.2} \times \exp\left(-\frac{3.22\rho}{\rho_G}\right) \exp\left(-\frac{r^2}{a^2}\right),$$  \hspace{1cm} (15)
where we take $h = 100$ pc, $R_\odot = 8$ kpc.

The spectrum evaluated at Earth’s position is the solid line shown in Figure 2. The model fits the data reasonably well and it is not coincident that the spectra join smoothly at the knee.

![Figure 2. CR spectrum at the Earth as a combination of the SNR contribution (in the Galactic disk) and the stochastic acceleration in the Fermi Bubbles. The black solid line is the spectrum from our numerical model. For the references to the experimental data see the original paper [17].](image)

6. Conclusion

We analyzed two groups of theoretical models of Fermi bubbles: hadronic and leptonic ones. We showed that hadronic models may experience some difficulties since long confinement of protons inside the bubbles is necessary.

Although at present we do not have reliable arguments observational evidences in favor of leptonic or hadronic origin of the gamma-ray emission from Fermi bubbles, it may be available in future from observations in the ranges below 100 MeV and above 1 TeV.

We also discussed connections between CRs in the bubbles and that seen at the Earth.

- If gamma-ray and radio emission from Fermi bubbles is produced by electrons accelerated in-situ, we cannot exclude that these electrons are emitted by SNRs which are re-accelerated in the halo. The point is that SN electrons propagate into halo. Processes of re-acceleration there provide particles with harder spectrum that explains the origin of gamma-ray and microwave emission from the bubbles. The advantage of this mechanism is that the energy of electrons is increased in two orders of magnitude only (cf. for acceleration of background electrons eleven orders of magnitude is needed). This source of accelerated particles is often overlooked despite being very efficient. Moreover, spatially uniform model involving reacceleration of the CR electrons overproduces gamma-ray emission from the Fermi bubbles. This effect does not depend on the particular choice of the reacceleration mechanism and only depends on the propagation model for the CR electrons. This fact may indicate on strong outflow in the Galactic center region or on the importance of the anisotropic diffusion in the region of Fermi bubbles or in the whole Galactic halo.

- As potential giant accelerators with age and size exceeding those of typical SNR by 3 orders of magnitude, Fermi bubbles can significantly distort spectrum of CR protons and nuclei observed near the Earth. in particular they may be responsible for formation of the spectrum of CRs beyond the “knee”. 
Acknowledgments

VAD and DOC are supported in parts by the grant RFBR 18-02-00075. DOC is supported in parts by foundation for the advancement of theoretical physics and mathematics “BASIS”. CMK is supported in part by the Ministry of Science and Technology of Taiwan under grants MOST 104-2923-M-008-001-MY3 and MOST 105-2112-M-008-011-MY3. KSC is supported by the GRF Grant under HKU 17310916.

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