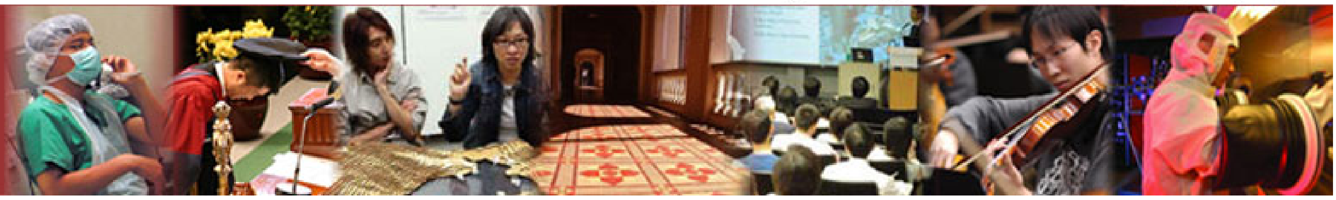

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Particle acceleration and the origin of gamma-ray emission from Fermi Bubbles

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Abstract: Fermi LAT has discovered two extended gamma-ray bubbles above and below the galactic plane. We propose that their origin is due to the permanent energy release in the Galactic center (GC) as a result of star accretion onto the central black hole. Shocks generated by these processes propagate into the Galactic halo and accelerate particles there. We show that electrons accelerated up to $\sim$ 10 TeV may be responsible for the observed gamma-ray emission of the bubbles as a result of inverse Compton (IC) scattering on the relic photons. We suggest that the Bubble could generate the flux of CR protons at energies $> 10^{15}$ eV because the shocks in the Bubble have much larger length scales and longer lifetime in comparison with those in SNRs. This may explain the the CR spectrum above the knee.

Keywords: Galaxy: halo – radiation mechanisms: non-thermal — acceleration of particles — shock waves

1 Introduction

Fermi bubbles are symmetric structures elongated above and below the Galactic plane for about 8 kpc [13]. Their discovery is one of the most remarkable events in astrophysics. The origin of the bubble is still enigmatic and up to now a few models were presented in the literature. The team, which subtracted this structured gamma-ray emission from the total diffuse galactic emission presented different explanations of the phenomenon though they seem to trend towards the model of a single huge energy release in the Galactic center (GC) when about 10 million years ago a huge cloud of gas or a star cluster was captured by the central black hole that produced the Fermi bubbles seen today. Later it was shown that electrons may be accelerated by the turbulence excited by Kelvin-Helmholtz instabilities [12]. Another interpretation was presented by [8] who proposed a relatively slow energy release ($\sim 10^{39}$ erg s^{-1}) due to supernova explosions as a source of proton production in the GC which emitted gamma-rays there.

An alternative explanation based on the assumption that the energy for the Fermi bubbles was originated from star capture events which occurred in the GC every $10^4 - 10^5$ years was suggested by [7]. About one thousands of such events form giant shocks propagating through the central part of the Galactic halo and thus produce accelerated particle responsible for the bubble emission. Processes of particle acceleration by the bubble shocks in terms of sizes of the envelope, maximum energy of accelerated particles, etc. may differ significantly from those obtained for SNs that may lead to the maximum energy of accelerated particles much larger than can be reached in SNRs. In this respect, we assume that acceleration of protons in Fermi bubbles may contribute to the total flux of the Galactic cosmic rays (CR) above the 'knee' break ($\geq 10^{15}$eV).

2 Structure of Shocks in the Fermi Bubble

As it was assumed in [7] the central massive black hole captures a star every $\tau_0 \sim 10^4 - 10^5$ years and as a result releases energy about $\mathcal{E}_0 \sim 10^{52}$ erg in the form of subrelativistic particles which heat the central ≤ 100 pc in the GC. This heating produces a shock propagating into the surrounding medium [15]. For exponential atmosphere with plasma density profile

$$\rho(z) = \rho_0 \exp\left(-\frac{z}{z_0}\right) , \quad (1)$$

an analytical solution for permanent energy injection by star accretion was obtained by [10]. Here z is the coordinate perpendicular to the Galactic plane. The radius of the bubble as a function of the height z and the time t is

$$r = 2z_0 \cos^{-1}\left[\frac{1}{2} e^{\frac{z}{2z_0}} \left(1 - \left(\frac{y}{2z_0}\right)^2 + e^{-\frac{z}{z_0}}\right)\right] , \quad (2)$$

where

$$y = \int\limits_0^t \left(\frac{\gamma^2 - 1}{2} \lambda \frac{\alpha W t}{V(t)\rho_0}\right)^{0.5} dt\,, \quad (3)$$

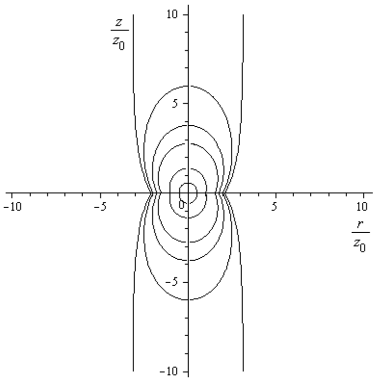

Figure 1: The bubble multi-shock structure.

V is a current volume enveloped by the shock

$$V(t) = 2\pi \int_0^{a(t)} r^2(z,t)dz\,, \quad (4)$$

a is the position of the shock top

$$a(t) = -2z_0 \ln\left(1 - \frac{y}{2z_0}\right)\,, \quad (5)$$

$W = \mathcal{E}_0/\tau_0$ is the average luminosity of the central source, γ is the polytropic coefficient, and α and λ are numbers [5].

Depending on capture parameters one can imagine the bubble interior as a volume filled with many shocks of different ages (see Fig.1).

For $W = 3 \cdot 10^{40}$ erg s^{-1}, $z_0 = 4$ kpc and $n_0 = 1$ cm^{-3}, the shock reaches the height $a = 8$ kpc for the time $t \sim 10^8$ yr. The average plasma temperature in the bubble interior is about $T \sim 1$ keV, the plasma density $n \sim 10^{-2}$ cm^{-3} and the maximum radius of the bubble $r_{max} \simeq 6$ kpc.

3 Particle Acceleration by the Bubble Shocks

Correct analysis of shock acceleration in the bubble requires sophisticated calculations of each stage of this process which we hope to perform later. Now we present simple estimates of characteristics of accelerated spectra. We analyze spectra of protons and electrons separately because they are formed by completely different processes and as we later conclude their spectral characteristics differ strongly from each other. We present also the spectrum of gamma-ray emission produced by inverse Compton (IC) scattering of the accelerated electrons in the bubble.

3.1 Proton Spectrum

Below we analyse the spectrum of protons accelerated in the bubble and discuss whether the bubble contribution to the total flux of CRs in the Galaxy may explain the knee steepening. We remind that the generally accepted point of view is that the flux of relatively low energy CRs ($< 10^{15}$eV) is generated by SNRs which ejects a power-law spectrum E^{-2} into the interstellar medium. This spectrum is steepened by propagation (escape) processes in the Galaxy in accordance with the spectrum observed near Earth (for details see [4]). However these sources can hardly produce CRs with energies more than 10^{15}eV (see [2, 3]). Just at this energy a steepening (the knee) in the CR spectrum is observed. We assume that the bubble may generate the flux of CRs at energies above 10^{15}eV. The origin of CRs with energies above 10^{15}eV is the goal of this subsection. It is natural to assume that the bubble shocks may produce this flux considering their large scales and long lifetimes.

In the framework of our model one can imagine the bubble as a volume of the radius 6 -10 kpc filled with hundreds of shocks propagating in series one after another. The frequency of shock injection (star capture) is poorly known parameter, especially for the conditions of the GC. From the analysis of shock hydrodynamics we estimated the age of outer shock by 10^8 yr though this value depends strongly on parameters of the self-similar solution which is a strong simplification of conditions in the Galaxy. The frequency of star capture by a central black hole is estimated from theoretical treatments $\nu \sim 10^{-4} - 10^{-5}$yr^{-1} [1]. Thus, a multi-shock structure can be produced by the capture processes with an average distance L between separate shocks given by

$$L = \tau_{cap}u = 30(\nu \times 3 \times 10^4 yr)(u/10^8 cm/s)pc. \quad (6)$$

On the other hand there is another spatial scale which characterizes processes of particle acceleration by a single shock which is $l_D \sim D/u$ where D is the spatial diffusion coefficient near a shock and u is the shock velocity. Depending on the relation between L and l_D there may be different regimes of acceleration in the bubble. This problem of particle acceleration in supersonic turbulence or multi-shock structure was analyzed in [6]. The acceleration regime is characterized by a dimensionless parameter

$$\psi = \frac{L}{l_D} = \frac{uL}{D}\,, \quad (7)$$

If $\psi << 1$, the diffusion length scale of a single shock l_D exceeds the distance between shocks L. Therefore, particle are accelerated by interactions with many shocks that gives the acceleration similar to the classical stochastic Fermi acceleration. The critical energy E_1 for this regime of acceleration is estimated from the condition $\psi \sim 1$ or $l(E_1) \sim L$. In the Bohm limit with the diffusion coefficient $D \sim cr_L(E)/3$ where $r_L(E) = E/eB$ is the particle Larmor, the value of E_1 is

$$E_1 \sim \frac{eBLu}{c} = 10^{15}\left(\frac{B}{5\mu G}\right)\left(\frac{L}{30pc}\right)\left(\frac{u}{10^8 cm/s}\right)\text{eV}. \quad (8)$$

which is about of the position of the knee break.

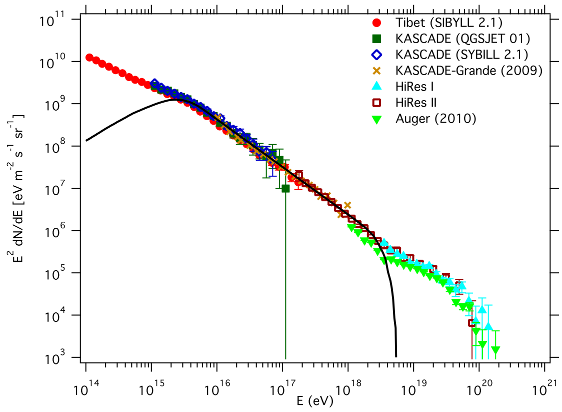

Figure 2: The Bubble contribution to the flux of CRs. The data are summarized in [11].

The kinetic equation for the case $\psi << 1$ ($E >> E_1$) converges to the diffusion in the spatial and momentum spaces (Fermi stochastic acceleration) in the form

$$\frac{\partial}{\partial z}D(\rho)\frac{\partial f}{\partial z}+\frac{1}{\rho}\frac{\partial}{\partial \rho}D(\rho)\rho\frac{\partial f}{\partial \rho}+\frac{1}{p^2}\frac{\partial}{\partial p}\kappa(\rho,p)p^2\frac{\partial f}{\partial p}=0 \quad (9)$$

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

$$\kappa \sim \frac{u^2}{cL}p^2 \quad (10)$$

The momentum dependence of f can be presented by a power-law function, $f(p) \propto p^{-\gamma}$, where γ should be determined from Eq.(9):

$$\gamma \simeq \frac{3}{2}+\sqrt{\frac{9}{4}+\frac{cLD_0}{u^2H^2}} \quad (11)$$

where H is the height of the Galactic halo and $D = D_0(E/E_0)^\xi$ is the average diffusion coefficient in the Galaxy. For $H \simeq 10$ kpc, $D_0 \simeq 10^{29}$ cm^{2}s^{-1}, $\xi \simeq 0.3$, $E_0 \simeq 3$ GeV [14] and $u = 10^8$ cm/s, $L = 100$ pc we have $\gamma \simeq 5$, i.e. the power-law spectrum above 10^{15} eV is in the form $N(E) \propto E^{-3}$ as necessary for the knee spectrum. The contribution of protons to the flux of the Galactic cosmic rays is shown in Fig. 2.

3.2 Electron Spectrum and Spatial Distribution

Unlike protons relativistic electrons lose their energy effectively by synchrotron and inverse Compton radiation. The rate of energy loss of electrons is

$$\frac{dE}{dt}=-\beta E^2=-c\sigma_T\left(w_H+w_{ph}\right)\left(\frac{E}{m_ec}\right)^2. \quad (12)$$

The maximum energy of electrons E_{max} can be estimated if the spatial diffusion coefficient at the shock D_{sh} is known. From Eq. (12) we have

$$E^e_{max} \sim \frac{u^2c}{\beta D_{sh}} \quad (13)$$

For the Bohm diffusion coefficient we can estimate the upper limit for E^e_{max} which is

$$E^e_{Bmax} \sim \sqrt{\frac{eHu^2}{3c\beta}}\,. \quad (14)$$

that gives for the velocity $u = 10^8$ cm s^{-1}, the magnetic field strength $H = 10^{-5}$ G and $w_{ph} = 0.25$ eV cm^{-3} the maximum energy of accelerated electrons about $E_{Bmax} \sim 5 \times 10^{13}$eV, i.e. for electrons $E < E_{Bmax} << E_1$. It follows from this inequality that electrons are accelerated in the regime $\psi >> 1$. Kinetic equations for this case were derived in [6].

In the case of electrons there is one more spatial parameter essential for acceleration by shocks, namely the electron mean free path λ. Therefore we have two more dimensionless parameters which describe electron acceleration in the case of supersonic turbulence, l_{sh}/λ and l_D/λ. Nearby shocks electrons propagate by diffusion, and λ there is a function of energy

$$\lambda_D(E) \sim \sqrt{\frac{D}{\beta E}} \quad (15)$$

From Eq. (13) one can see that for $E < E^e_{max}$ we have $\lambda > l_D$ i.e. acceleration by shocks is effective.

Far away from shocks electrons propagate by convection and for the velocity u the mean free path is

$$\lambda_V(E) \sim \frac{u}{\beta E} \quad (16)$$

For relatively low energy electrons $\lambda(E) > l_{sh}$, and a regime of multi-shock acceleration for electrons is realized in this case where interactions with many shocks change slowly the shock to E^{-1} (for details see [6]) which produces a hard E^{-1} spectrum . The break position E^* between the single shock and multi-shock spectra follows from the equality $\lambda(E^*) = l_{sh}$

$$E^* \sim \frac{u}{\beta l_{sh}} \quad (17)$$

that gives e.g. $E^* \sim 2.8 \times 10^{11}$ eV for $l_{sh} = 10^{21}$ cm.

If we assume that the bubble gamma-rays are produced by IC scattering of electrons on the relic photons, then it follows from our model that: 1. the drop of the bubble gamma-ray flux at $E_\gamma < 1$ GeV as observed by [13] is due to a flattening of electron spectrum at $E < E^*$; and 2. a drop of this spectrum in the range $E_\gamma > 100$ GeV is due to a cut-off in the electron spectrum at $E \sim E^e_{max}$. The expected spectrum of gamma-ray emission from the Bubble due to IC scattering of the electrons is shown in Fig. 3.

Spatial distribution of the gamma-ray emission in case of single shock and in case of N uniformly spaced shocks separated by distance L is shown in Fig. 4. For the multiple shocks it was assumed that they fill only the outer part of the Bubble, i.e., they are located at distances 3 kpc, 3

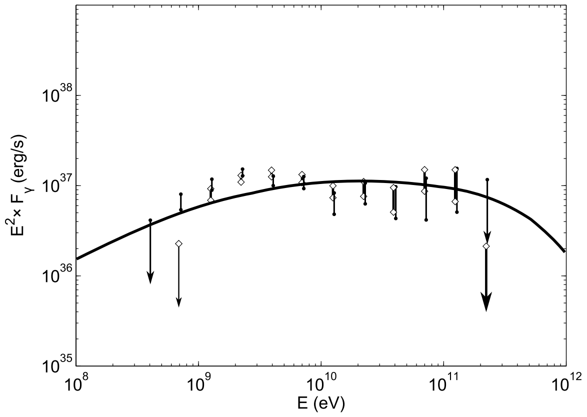

Figure 3: The spectrum of gamma-ray emission from Fermi bubble in case of multi-shock acceleration. Data points are taken from [13].

kpc $-l_{sh}$, ..., 3 kpc $-N \cdot l_{sh}$ from the center of the Bubble. One can see that in case of single shock and in case when the bubble volume is uniformly filled with 30 shocks ($N = 30$, dash-dotted line) the fitting of the experimental data is not very good. The spatial distribution is reproduced well if the number of shocks is around 15 (dashed line), i.e., if shocks fill only the outer 1-2 kpc of the Bubble (see also [12]).

4 Conclusion

We have shown that series of shocks produced by a sequential stellar captures by the central black hole can further accelerate the protons up to energies above $10^{15} eV$. It is quite difficult to achieve these energies in supernovae due to the limited acceleration time and length scale of SN shocks. The predicted CR spectrum contributed by the Bubble may be $E^{-\nu}$ where $\nu \sim 3$ for 10^{15} eV $< E < 10^{19}$ eV that explains the knee CR spectrum.

The regime of electron acceleration in the bubble is quite different from that of protons, which is a combination of single and multishock accelerations. In this case we have a cut-off of the electron spectrum at $E > 3\ 10^{13}$ eV and flattening of the spectrum at $E < 100$ GeV that explains nicely the bubble gamma-ray spectrum observed by [13] if this emission is due to IC on the relic photons

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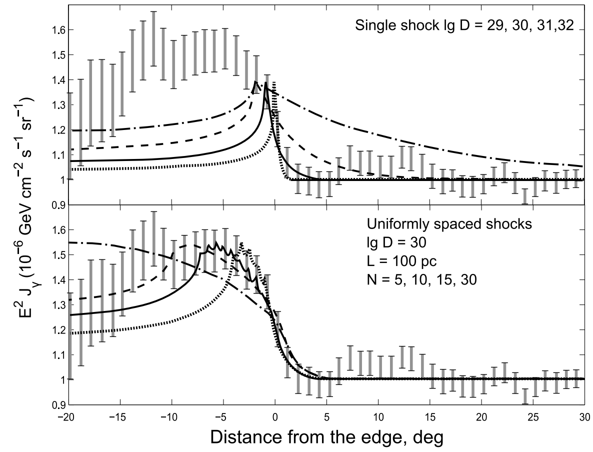

Figure 4: Spatial distribution of the gamma-ray emission. Data are from [13]. *Top:* in case of single shock. Dotted line correspond to D=10^{29} cm^2/s, solid to D=10^{30} cm^2/s, dashed to D=10^{31} cm^2/s and dash-dotted D=10^{32} cm^2/s, *Bottom:* in case of several uniformly spaced shocks separated by distance $L = 100$ pc. Dotted line corresponds to amount of shocks $N = 5$, solid line to $N = 10$, dashed line to $N = 15$ and dash-dotted line to $N = 30$.

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