Fermi Bubbles as a Result of Star Capture in the Galactic Center

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Fermi has discovered two giant gamma-ray-emitting bubbles that extend nearly 10 kpc in diameter. We propose that periodic star capture processes by the galactic supermassive black hole, Sgr A*, with a capture rate $< 10^{-3}$ yr$^{-1}$ and energy release $\sim 10^{52}$ erg per one capture can produce shocks in the halo, which accelerate electrons to the energy $\sim 1$ TeV. These electrons generate radio emission via synchrotron radiation, and gamma-rays via inverse Compton scattering with the relic and the galactic soft photons. Estimates of the diffusion coefficient from the observed gamma-ray flux explains consistently the necessary maximum energy of electrons and sharp edges of the bubble.

I. INTRODUCTION

The recently discovered Fermi bubbles are symmetric gamma-ray structures derived from the Fermi LAT data in the energy range 1-100 GeV. The bubbles elongate above and below the Galactic plane for about 8 kpc and their radius is about 3 kpc. Observations show a very sharp outer boundary of the bubble. The gamma-ray intensity sharply drops outward the bubbles.

The origin of the bubble is still enigmatic and up to now a few models were presented in the literature. Our group assumed that the Fermi bubbles originated from star capture events which occurred in the GC every $10^4 - 10^5$ years \cite{2}. These events form giant shocks propagating through the central part of the Galactic halo and thus produce accelerated electrons with energies $\leq 10$ TeV whose scattering on background photons is responsible for the bubble gamma-ray 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 protons 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).

II. BUBBLE HYDRODYNAMICS

We assume in \cite{2} that the central black hole captures a star every $\tau_0 \sim 10^4 - 10^5$ years. As a result, the total energy $\mathcal{E}_0 \sim 10^{52}$ erg releases in the Galactic center in the form of 100 MeV proton which heat the central 20 pc up to the temperature $\sim 10$ keV. This heating produces a shock propagating into the surrounding medium. In the simplest case this situation can be described by a solution obtained by \cite{3} for the adiabatic explosion in the exponential atmosphere with the density profile $\rho(z)$,

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

where $z$ is the coordinate perpendicular to the Galactic plane. For parameters of the Galactic halo $\rho_0 = 0.25$ cm$^{-3}$ and $z_0 = 1$ kpc. The shock propagating into the halo forms in the exponential atmosphere a double bubble structure elongated in z-direction. The radius of the bubble at the height $z$ and at the time $t$ is

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

where

$$y = \int_0^t \left( \frac{\gamma^2 - 2}{2} - \frac{1}{2} \lambda \frac{\alpha \mathcal{E}_0}{V(t)\rho_0} \right)^{0.5} dt,$$

$V$ is a current volume bounded by the shock

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

$a$ is the position of the shock top

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

$\gamma$ is the polytropic coefficient, and $\alpha$ and $\lambda$ are numbers.

For the finite time $t_1$ determined from the condition $y(t_1) = 2z_0$ the shock breaks through the exponential atmosphere and the bubble top $a(t_1)$ tends to infinity.
while the bubble radius in the Galactic plane \((z = 0)\) tends asymptotically to the value
\[
  r = 2z_0 \arccos (1/2) \simeq 2 \text{ kpc},
\]  
that is comparable with the radius of Fermi bubbles. For \(E_0 \sim 10^{52} \text{ erg} \) and \(\rho_0 \sim 0.25 \text{ cm}^{-3}\) the value of \(t_1\) is about \(3 \times 10^8 \text{ yr}\). We want to remark that \(t_1\) sensitively depends on the injected energy and the density profile of the halo. For example if the injected energy is \(E_0 \sim 3 \times 10^{52} \text{ erg} \) and \(\rho_0 \sim 0.1 \text{ cm}^{-3}\), \(t_1\) can be reduced by nearly an order of magnitude.

Then for a periodic star capture the bubble interior is filled with shocks propagating in series one after another through the bubble interior stopping at the radius \(z_0\) That gives formally a stationary sideway boundary.

The realistic situation has to be described by a set of dissipative hydrodynamic equations, which take into account the shocks propagation in non-uniform medium and various dissipation processes including shock heating, energy transfer into cosmic rays, slowing down due to accumulating material etc. These processes are ignored in the the Kompaneetz solution. Shocks should disappear when their speed is lower the local sound speed. shocks should disappear when their speed is lower the local sound speed. Then the sideway boundary of the Bubble is simply given by \(r_b \sim v_s t_{dis}\) where \(v_s\) is the sound speed and \(t_{dis}\) is the characteristic time of the shock dissipation because of e.g. particle acceleration at the shock front.

III. ELECTRON ACCELERATION AND GAMMA-RAYS FROM THE BUBBLE

We assume that the bubble gamma-rays are produced by IC scattering of electrons on the relic photons. For the rate of synchrotron and inverse Compton energy losses \(dE/dt = \beta E^2\) the maximum energy of electrons \(E_{\text{max}}^e\) accelerated by shocks estimated in the Bohm diffusion limit is
\[
  E_{\text{max}}^e \sim \sqrt{\frac{eH u^2}{3c\beta}}.
\]
that gives e.g. for the shock velocity \(u = 10^8 \text{ cm s}^{-1}\), the magnetic field strength \(H = 10^{-5} \text{ G}\) and the energy density of relic photons \(w_{ph} = 0.25 \text{ eV cm}^{-3}\) the maximum energy of accelerated electrons about \(E_{\text{max}}^e \sim 5 \times 10^{13} \text{ eV}\).

In Fig. 1 we show the expected spatial distributions of gamma-ray emission from the bubble for single shock and multiple shocks cases. From this figure one can see that the single shock model is unable to reproduce the data. However, for the parameters of star capture model these data are nicely described.

The expected spectrum of gamma-ray emission from the Bubble due to IC scattering of the electrons is shown in Fig. 2.

IV. PROTON ACCELERATION IN THE BUBBLE AND THE ORIGIN OF THE "KNEE" COSMIC RAYS

CRs within with energies below \(E \sim 10^{15} \text{ eV}\) are generally attributed to SNRs in our Galaxy. We assume that some of the CRs produced by SNRs in the Galactic disk are re-accelerated by shocks in the Bubble to energy above \(10^{15} \text{ eV}\) that explains the origin of CRs beyond the knee.

For the multi-shock structure in the bubble an average distance \(L\) between separate shocks given by
\[
  L = \tau_0 u = 30 \left( \frac{\tau_0}{3 \times 10^4 \text{yr}} \right) \left( \frac{u}{10^8 \text{ cm/s}} \right) \text{ pc}.
\]
If the value of $L$ exceeds the scale 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, then particle acceleration by shocks is pure stochastic, which describes by a momentum diffusion coefficient (see [4])

$$\kappa \sim \frac{u^2}{cL}p^2.$$  \hspace{1cm} (9)

Then the equation describing particle production by SNRs in the disk, their re-acceleration in the bubble and propagation in the Galaxy can be presented in the form

$$\frac{\partial}{\partial z} \left( D(\rho, p) \frac{\partial f}{\partial z} \right) + \frac{1}{\rho} \frac{\partial}{\partial \rho} \left( D(\rho, p) \rho \frac{\partial f}{\partial \rho} \right) + \frac{1}{p^2} \frac{\partial}{\partial p} \left( \kappa(\rho, p)p^2 \frac{\partial f}{\partial p} \right) = -Q(\rho, z, p), \hspace{1cm} (10)$$

where $\rho$ and $z$ are the cylindrical spatial coordinates, $p$ is the particle momentum. $D(\rho, p)$ is the spatial diffusion coefficient, which is a function of coordinates and particle momentum, and $Q(\rho, z, p)$ describes CR injection by supernova remnants in the disk with energies $E < 10^{15} \text{ eV}$ with the spectrum $Q \propto p^{-4}$. The spectrum of CRs injected by SNRs and re-accelerated in the bubble is shown in Fig. 3.

V. CONCLUSION

We have shown that series of shocks produced by a sequential stellar captures by the central black hole can further re-accelerate the protons emitted by SNRs up to energies above $10^{15} \text{ eV}$. The predicted CR spectrum contributed by the Bubble may be $E^{-\nu}$ where $\nu \sim 3$ for $10^{15} \text{ eV} < E < 10^{19} \text{ eV}$ that explains the knee CR spectrum.

The regime of electron acceleration in the bubble is quite different from that of protons. It is a combination of single and multishock accelerations. In this case we have a cut-off of the electron spectrum at $E > 3 \times 10^{13} \text{ eV}$ and flattening of the spectrum at $E < 100 \text{ GeV}$ that explains nicely the bubble gamma-ray spectrum and the sharp edge spatial distribution observed by [1] if this emission is due to IC on the relic photons.

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