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Gamma rays from Fermi bubbles as due to diffusive injection of Galactic cosmic rays

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ABSTRACT

Recent detailed analysis of the Fermi-LAT data has discovered two giant $\gamma-$ray emission regions, the so-called Fermi bubbles, extending up to $\sim 50^\circ$ in Galactic latitude above and below the Galactic center with a width of $\sim 40^\circ$ in longitude. The origin of the $\gamma-$ray emission is not clearly understood. Here, we discuss the possibility that the $\gamma-$rays can be the result of diffusive injection of Galactic cosmic-ray protons during their propagation through the Galaxy. In the model, we consider that the bubbles are slowly expanding, and cosmic rays undergo much slower diffusion inside the bubbles than in the averaged Galaxy. Moreover, we consider that cosmic rays inside the bubbles suffer losses from adiabatic expansion, and also from inelastic collisions with the bubble plasma producing pion-decay γ rays. We show that this simple model can explain some of the important properties of Fermi bubbles such as the measured $\gamma-$ray intensity profile, the energy spectrum and the measured luminosity.

1. Introduction

The *Fermi* space telescope has recently discovered two large $\gamma-$ray emitting regions that extend up to $\sim 50^\circ$ in the Galactic latitude both above and below the Galactic center, and $\sim 40^\circ$ in longitude [1]. These regions, commonly known as the "Fermi bubbles", are spatially coincident with the microwave haze [2–4], and share their boundaries with the ROSAT X-ray map [5]. They are also found to coincide with two giant radio lobes originating from the Galactic center [6]. This multi-wavelength correlation tends to suggest that the Fermi bubble $\gamma-$rays are of leptonic origin, i.e., produced by high-energy electrons through inverse Compton scattering process, as the same electron population can also simultaneously produce synchrotron radiations at low frequencies [7]. Also, the positional symmetry of the Fermi bubbles both with respect to the Galactic plane and the Galactic center seems to indicate that the origin of the bubbles and their $\gamma-$ray emission lies at the Galactic center.

But, the severe radiative losses suffered by high-energy electrons pose a problem for the leptonic model. For instance, for 1 TeV electrons (which are responsible for producing the observed $\gamma-$rays of energies ~ 100 GeV), their synchrotron loss time in an averaged magnetic field strength of 4 μG in the Galaxy is $\sim 7\times 10^5$ yr. Therefore, transporting such electrons by Galactic winds from the Galactic center to reach the far edge of the bubbles, which is at ~ 10 kpc away, would require a wind speed of over 10^4 km s^{-1}. This speed is over an order of magnitude larger than the typical wind speed in the Galaxy. And transport by the diffusion process would require a diffusion coefficient of over two to three orders of magnitude larger than that in the Galaxy. Nevertheless, there are models which can overcome this difficulty. They are based on intense jet activity of the central active galactic nucleus [8,9], periodic star capture by the central supermassive black hole [10], and second-order Fermi acceleration inside the bubbles [11]. Hadronic models, on the other hand, are not tightly constrained by the injection problem. Crocker and Aharonian [12] claimed that cosmic-ray nuclei transported by high-speed wind from the Galactic center can explain the Fermi bubble $\gamma-$rays if the particles remain confined for multi-billion years inside the bubbles.

In this paper, we discuss a simple model which does not involve any additional process of particle production other than those responsible for the production of Galactic cosmic rays [13]. The model assumes that cosmic-rays, mainly protons, are produced by sources such as supernova remnants in the Galaxy. After liberating from their sources, cosmic rays undergo diffusive propagation through the Galaxy due to scattering either by magnetic turbulence present in the Galaxy or by self-generated Alfvén waves. During propagation, some of the cosmic rays can get injected diffusively into the bubbles. This injection is governed by the density gradient toward the bubbles which we assume to exist considering that the bubbles are absent of cosmic-ray sources. In addition, if the bubbles are expanding, there will also be an additional injection of cosmic rays as the bubble surface swept through the interstellar medium. The amount of this injection will

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depend on the expansion velocity of the bubbles. If we consider that the injection is uniform throughout the surface of the bubble, the total amount of cosmic-ray power injected into each bubble is given by $4\pi R^2 u\varepsilon$, where we assume the bubble as a sphere of radius R, u is the cosmic-ray injection velocity, and ε represents the cosmic-ray energy density. For cosmic-rays injection at the Alfvén velocity $v_A \sim 100$ km s^{-1}, which is the maximum streaming velocity the particles can have in the case of scattering by self-generated waves, the total amount of cosmic-ray power injected is $\sim 4\times 10^{40}$ erg s^{-1} for R=4.5 kpc and the measured cosmic-ray energy density of $\varepsilon = 1$ eV cm^{-3}. This amount of power is approximately two orders of magnitude larger than the power required in cosmic-ray protons to produce the measured γ−ray luminosity which is $\sim 2\times 10^{37}$ erg s^{-1} from each bubble. This shows that the injection of some fraction of Galactic cosmic-rays will be sufficient to explain the measured γ−ray luminosity.

For diffusive injection, the injection flux is given by $D_g \nabla N_g \propto D_g N_g$, where D_g and N_g are the diffusion coefficient and the number density of cosmic rays in the Galaxy respectively. As $N_g \propto Q/D_g$, where Q is the cosmic-ray source spectrum in the Galaxy, the injection flux is proportional to Q. Inside the bubbles, we assume that cosmic rays undergo much slower diffusion than in the averaged Galaxy. This can be realized if the plasma inside the bubbles are highly turbulent [14] or the magnetic field lines in the region are highly tangled [15]. We further assume that cosmic rays are also convected radially outward by the expanding plasma. If convection dominates, cosmic rays will follow a distribution that peaks toward the edge of the bubbles. Moreover, if the diffusion length inside the bubbles is much less than the size of the bubble, the shape of the total cosmic-ray spectrum will follow that of the injection spectrum.

The interaction of cosmic-ray protons with the bubble plasma can generate continuous production of secondary electrons and positrons inside the bubbles. These electrons and positrons can produce synchrotron emissions that are observable at radio and microwave frequencies. The energy spectrum of such electrons/positrons suffering continuous radiative losses follows $E^{-\Gamma}$ for $E < E_c$, and $E^{-\Gamma-1}$ for $E > E_c$, where E represents the electron energy, E_c is the energy at which the energy loss time equals the age of the bubble, and Γ is the index of the electron production spectrum which in our case is equal to the cosmic-ray source index in the Galaxy. The recently reported hard electron spectrum of index $\sim$2.1, which is required to produce the observed microwave emission spectrum between 23 and 61 GHz [4], can be explained in our model if the emitting electrons have energies less than E_c.

2. Cosmic-ray spectrum inside the bubbles

In the comoving frame of expansion, the distribution of cosmic-ray protons inside a bubble can be described by a one-dimensional diffusion-loss equation as [13]

$$\frac{d}{dx}\left(D_b \frac{dN_b}{dx}\right) - \frac{N_b}{\tau} = 0 \tag{1}$$

where x represents the spatial coordinate measured from the bubble boundary with $x > 0$ ($x < 0$) representing the region inside (outside) the bubble, $N_b(x, E)$ represents the cosmic-ray number density, E is the kinetic energy, and $D_b(E)$ represents the diffusion coefficient. The particle loss time $\tau(E)$ is given by $1/\tau = 1/\tau_{ad} + 1/\tau_{pp}$, where $\tau_{ad} = 3R/2U$ represents the adiabatic loss time due to the volume expansion, $\tau_{pp}(E) = 1/(n_b v\sigma)$ represents the inelastic collision time with the bubble plasma of density n_b, v the particle velocity, and $\sigma(E)$ the inelastic collision cross-section. In Eq. (1), we assume that the bubble expands with constant velocity, and we have treated the adiabatic energy loss as a catastrophic loss process.

Using the boundary condition that the particle density must be finite at $x = \infty$, together with the flux conservation relation at the bubble boundary, the solution of Eq. (1) can be obtained as

$$N_b(x, E) = \left(F_{dif} + F_{exp}\right)\sqrt{\frac{\tau}{D_b}}\, e^{-x/\sqrt{\tau D_b}} \tag{2}$$

where $F_{dif} = D_g dN_g/dx|_{x=0}$ is the diffusive injection flux of Galactic cosmic rays into the bubble, and $F_{exp} = UN_g|_{x=0}$ is the injection flux due to sweeping of the ambient cosmic rays by the expanding bubble. Eq. (2) can be expressed in terms of the radial coordinate r measured from the center of the bubble by replacing x with $R - r$.

The injection fluxes are estimated as follows. First, we write the Galactic cosmic-ray density as a function of perpendicular distance z to the Galactic plane as [16]

$$N_g(z, E) \propto \frac{Q(E)}{D_g(E)} f_1(z) \tag{3}$$

where $Q(E)$ and $D_g(E)$ represent the cosmic-ray source spectrum and the diffusion coefficient in the Galaxy respectively, and the function $f_1(z)$ depends weakly on energy. Based on the measured boron-to-carbon ratio, we obtain $D_g = D_0(E/3\ \text{GeV})^{0.6}$ with $D_0 = 6\times 10^{28}$ cm^2 s^{-1}, for a diffusion halo size of 10 kpc.

The cosmic-ray density gradient along z can be obtained as

$$\frac{dN_g}{dz} \propto \frac{Q(E)}{D_g(E)} \frac{df_1}{dz}. \tag{4}$$

From Eq. (4), it can be noticed that

$$D_g \frac{dN_g}{dz} \propto Q(E) \tag{5}$$

which shows that F_{dif} follows the source cosmic-ray spectrum as mentioned in the previous section.

The injection flux due to expansion F_{exp} follows the ambient cosmic-ray spectrum N_g, and therefore is expected to be steeper than F_{dif}. To estimate F_{exp}, we determine the expansion velocity using the combined *Planck*-WMAP measurements of microwave emissions in the frequency range of 23–61 GHz [4]. For magnetic field strength of $B = 2.2\ \mu$G inside the bubbles, the highest measured frequency of 61 GHz would be emitted by electrons of energy 51 GeV (assuming that the emission is at critical frequency). The magnetic field is obtained at a distance of z=5 kpc using the relation $B(z) = 6e^{-z/5\text{kpc}}\ \mu$G [17]. As the *Planck*-WMAP data does not show any break in the spectrum up to 61 GHz, it implies that the age of the bubble must be less than the energy loss time of 51 GeV electrons which is estimated to be 5.26×10^7 yr. This gives a lower limit on the expansion velocity of the bubble at U=83 km s^{-1} for the present bubble radius of 4.5 kpc.

We neglect the possible variations of cosmic-ray injection over the surface of the bubble, and assume a uniform injection that corresponds to the injection flux at z=5 kpc. The total injection flux is then taken as $C[F_{dif} + F_{exp}]_{z=5\ \text{kpc}}$, where C is a constant that will take care of the unknown actual fraction of cosmic rays injected, and its value will be determined based on the measured γ−ray data. We further assume that the cosmic-ray diffusion coefficient scales inversely with the magnetic field strength in the Galaxy as $D_0(z) = 6\times 10^{28} e^{z/5\ \text{kpc}}$ cm^2 s^{-1}. This gives a value of $D_0 = 16\times 10^{28}$ cm^2 s^{-1} at a halo height of z=5 kpc. For this value of D_0 and U at z=5 kpc obtained above, the injection flux is found to be dominated by F_{dif} for energies above $\sim$1 GeV.

The cosmic-ray diffusion coefficient inside the bubble is assumed to follow $D_b = K\times 10^{28}(E/3\ \text{GeV})^{0.33}$ cm^2 s^{-1}, where the constant $K \ll 1$, and the cosmic-ray source spectrum is taken to have a broken power-law with indices $\Gamma = 2.2$ and 2.09 below and