ORIGIN OF THE FERMI BUBBLE

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ABSTRACT

Fermi has discovered two giant gamma-ray-emitting bubbles that extend nearly 10 kpc in diameter north and south of the Galactic center. The existence of the bubbles was first evidenced in X-rays detected by ROSAT and later WMAP detected an excess of radio signals at the location of the gamma-ray bubbles. We propose that periodic star capture processes by the galactic supermassive black hole, Sgr A*, with a capture rate $3 \times 10^{-7}$ yr$^{-1}$ and energy release $\sim 3 \times 10^{44}$ erg per capture can produce very hot plasma $\sim 10$ keV with a wind velocity $\sim 10^8$ cm s$^{-1}$ injected into the halo and heat up the halo gas to $\sim 1$ keV, which produces thermal X-rays. The periodic injection of hot plasma can produce shocks in the halo and accelerate electrons to $\sim$TeV, which produce gamma-ray emission via synchrotron radiation and gamma rays via inverse Compton scattering with the relic and the galactic soft photons.

Key words: black hole physics – galaxies: jets – Galaxy: halo – radiation mechanisms: non-thermal

1. INTRODUCTION

Observations reveal evidence of unusual processes occurring in the region of Galactic center (GC). For instance, there was an enigmatic 511 keV annihilation emission discovered by INTEGRAL (see, e.g., Knoedlseder et al. 2005) whose origin is still debated; and there is hot plasma with a temperature about 10 keV that cannot be confined in the GC and, therefore, sources with a power about $10^{41}$ erg s$^{-1}$ are required to heat the plasma (Koyama et al. 2007). In fact, plasma outflows with the velocity $\gtrsim 100$ km s$^{-1}$ are observed in the nucleus regions of our Galaxy (Crocker et al. 2010a) and Andromeda (Bogdan & Gilfanov 2010). Time variations of the 6.4 keV line and X-ray continuum emission are observed in the direction of molecular clouds in the GC which are supposed to be a reflection of a giant X-ray flare that occurred several hundred years ago in the GC (Inui et al. 2009; Ponti et al. 2010; Terrier et al. 2010). HESS observations of the GC in the TeV energy range indicated an explosive injection of cosmic rays (CR) there, which might be associated with the supermassive black hole (SMBH) Sgr A* (e.g., Aharonian et al. 2006).

Recent analysis of Fermi/LAT data (see Su et al. 2010; Dobler et al. 2010) discovered new evidence of GC activity. They found two giant features of gamma-ray emission in the range 1–100 GeV, extending 50 deg ($\sim 10$ kpc) above and below the GC—the Fermi bubble (FB). They presented a list of mechanisms that may contribute to the energy release and particle production necessary to explain the gamma-ray emission from the bubble. They noticed, however, that most likely the FB structure was created by some large episode of energy injection in the GC, such as a past accretion event onto the central SMBH in the last $\sim 10$ Myr. They cast doubt on the idea that the FB was generated by previous starburst activity in the GC because there was no evidence of massive supernova (SN) explosions ($\sim 10^4$–$10^5$) in the past $\sim 10^7$ yr toward the GC. Besides, these SN remnants should be traced by the line emission of radioactive $^{26}$Al. Observations do not show significant concentration of $^{26}$Al line toward the GC (Diehl et al. 2006).

Crocker & Aharonian (2011) and Crocker et al. (2010a, 2010b) argued that the procedure used by Su et al. (2010) did not remove contributions of CR interaction with an ionized gas, so gamma rays could be produced by proton interactions with the fully ionized plasma in the halo. Crocker & Aharonian (2011) also argued that the lifetime of these protons can be very long because the plasma is extremely turbulent in this region, therefore protons could be trapped there for a timescale $t_{pp} \gtrsim 10^{10}$ yr, and then the observed gamma rays can be explained with an injected power of SN $\sim 10^{39}$ erg s$^{-1}$.

In this Letter, we propose that the FB emission may result from star capture processes, which have been developed by Cheng et al. (2006, 2007) and Dogiel et al. (2009a, 2009c, 2009d) to explain a wide range of X-ray and gamma-ray emission phenomena from the GC.

2. OBSERVATIONS

The procedure of separation of the bubble emission from the total diffuse emission of the Galaxy is described in Su et al. (2010). It is important to note that the bubble structure is seen when components of gamma-ray emission produced by CR interaction with the background gas, i.e., by CR protons ($\pi^0$ decay) and electrons (bremsstrahlung), are removed. Su et al. (2010) concluded that the bubble emission was of inverse Compton (IC) origin generated by relativistic electrons. Here, we summarize the multi-wavelength observational constraints of the FB.

1. The spectral shape and intensity of gamma rays are almost constant over the bubble region, which suggests a uniform production of gamma rays in the FB. The total gamma-ray flux from the bubble at energies $E_\gamma > 1$ GeV is $F_{\gamma} \sim 4 \times 10^{-7}$ erg s$^{-1}$, and the photon spectrum of gamma rays is power law, $dN_\gamma/dE_\gamma \propto E_\gamma^{-2}$, for the range 1–100 GeV (Su et al. 2010).

2. In the radio range, the bubble is seen from the tens GHz WMAP data as a microwave residual spherical excess (“the microwave haze”) above the GC $\sim 4$ kpc in radius (Finkbeiner 2004). Its power spectrum in the frequency range 23–33 GHz is described as power law, $\Phi_\nu \propto \nu^{-0.5}$. For the magnetic field strength $H \sim 10$ $\mu$G, the energy of electrons responsible for emitting these radio waves...
is within the range 20–30 GeV and their spectrum is 
\(dN_p/dE_p \propto E_p^{-2}\).

3. The ROSAT 1.5 keV X-ray data clearly showed the characteristic of a bipolar structure (Bland-Hawthorn & Cohen 2003) that aligned well with the edges of the FB. The ROSAT structure is explained as due to a fast wind that drove a shock into the halo gas with the velocity \(v_{sh} \sim 10^8\) cm s\(^{-1}\). This phenomenon requires an energy release of about \(10^{55}\) erg at the GC, and this activity should be periodic on a timescale of 10–15 Myr.

4. The similarities of the morphology of the radio, X-ray, and gamma-ray structures strongly suggest their common origin.

In the case of electron (leptonic) model of Su et al. (2010), gamma rays are produced by scattering of relativistic electrons on background soft photons, i.e., relic, IR, and optical photons from the disk.

3. THE BUBBLE ORIGIN IN A MODEL OF A MULTIPLE STAR CAPTURE BY THE CENTRAL BLACK HOLE

In this section, we present our ideas about the origin of the FB in the framework of star capture by the central SMBH. The process of gamma-ray emission from the bubble is determined by a number of stages of energy transformation. Each of these stages actually involves complicated physical processes. The exact details of these processes are still not understood very well. Nevertheless, their qualitative features do not depend on these details. In the following, we only briefly describe these processes and give their qualitative interpretations. We begin by describing processes of star capture by the central black hole as presented in Dogiel et al. (2009d).

3.1. Star Capture by the Central Black Hole

As observations show, there is an SMBH (Sgr A\(^*\)) in the center of our Galaxy with a mass of \(\sim 4 \times 10^6\)\(M_\odot\). A total tidal disruption of a star occurs when the penetration parameter \(b^{-1} > 1\), where \(b\) is the ratio of the periapse distance \(r_p\) to the tidal radius \(R_t\). The tidal disruption rate \(v_t\) can be approximated to within an order of magnitude, \(v_t \sim 10^{-9}\) to \(10^{-3}\) yr\(^{-1}\) (see the review of Alexander 2005).

The energy budget of a tidal disruption event follows from analysis of star matter dynamics. Initially about 50% of the stellar mass becomes tightly bound to the black hole, while the remaining 50% of the stellar mass is forcefully ejected (see, e.g., Ayal et al. 2000). The kinetic energy carried by the ejected debris is a function of the penetration parameter \(b^{-1}\) and can significantly exceed that released by a normal SN (\(\sim 10^{51}\) erg) if the orbit is highly penetrating (Alexander 2005),

\[
W \sim 4 \times 10^{52} \left(\frac{M_*}{M_\odot}\right)^2 \left(\frac{R_\odot}{R_*}\right)^{-1} \left(\frac{M_{bh}/M_*}{10^6}\right)^{1/3} \left(\frac{b}{0.1}\right)^{-2} \text{erg}.
\]  

(1)

Thus, the mean kinetic energy per escaping nucleon is estimated as \(E_{\text{esc}} \sim 42(\frac{n_{0.5}}{n_0})^{-1/3}(\frac{M_\odot}{M_*})(\frac{R_\odot}{R_*})^{-1}(\frac{M_{bh}/M_*}{10^6})^{1/3}(\frac{b}{0.1})^{-2}\) MeV, where \(n_0 M_*\) is the mass of the escaping material. From \(W\) and \(v_t\) we obtain the average power in the form of a flux of subrelativistic protons. If \(W \sim 3 \times 10^{32}\) erg and \(v_t \sim 3 \times 10^{-3}\) yr\(^{-1}\), we get \(W \sim 3 \times 10^{40}\) erg s\(^{-1}\).

In Dogiel et al. (2009c), we described the injection spectrum of protons generated by processes of star capture as monoenergetic. This is a simplification of the injection process because a stream of charged particles should be influenced by different plasma instabilities, as it was shown by Ginzburg et al. (2004) for the case of relativistic jets. At first the jet material is moved by inertia. Then due to the excitation of plasma instabilities in the flux, the particle distribution functions, which were initially delta functions both in angle and in energy, transform into complex angular and energy dependencies.

3.2. Plasma Heating by Subrelativistic Protons

Subrelativistic protons lose their energy mainly by Coulomb collisions, i.e., \(dE_p/dt = -\frac{4\pi e^4}{m_p c} n_A \ln \Lambda\), where \(v_p\) is the proton velocity, and \(\ln \Lambda\) is the Coulomb logarithm. In this way the protons transfer almost all of their energy to the background plasma and heat it. This process was analyzed in Dogiel et al. (2009c, 2009d). For the GC parameters, the average time of Coulomb losses for several tens MeV protons is several million years. The radius of the plasma heated by the protons is estimated from the diffusion equation describing propagation and energy losses of protons in the GC (Dogiel et al. 2009b). This radius is about 100 pc. The temperature of heated plasma is determined by the energy that these protons transfer to the background gas. For \(W \sim 10^{40}-10^{41}\) erg s\(^{-1}\), the plasma temperature is about 10 keV (Koyama et al. 2007), as has been observed by Suzaku for the GC. The plasma with such a high temperature cannot be confined at the GC, and therefore, it expands into the surrounding medium.

3.3. The Hydrodynamic Expansion Stage

Hydrodynamics of gas expansion was described in many monographs and reviews (see, e.g., Bisnovatyi-Kogan & Silich 1995). As the time of star capture may be smaller than the time of proton energy losses, we have almost stationary energy release in the central region with a power \(W \sim 3 \times 10^{40}\) erg s\(^{-1}\). This situation is very similar to that described by Weaver et al. (1977) for a stellar wind expanding into a uniform density medium. The model describes that a star at time \(t = 0\) begins to blow a spherically symmetric wind with a stellar wind velocity of \(V_w\), mass-loss rate \(dM_w/dt = M_w\), and a luminosity \(L_w = M_w V_w^2/2\), which is analogous to the power \(W\) produced by star capture processes. Most of the time of the evolution is occupied by the so-called snowplow phase when a thin shock front is propagating through the medium. The shock is expanding as

\[
R_{sh}(t) = \alpha \left(\frac{L_w t^3}{\rho_0}\right)^{1/5},
\]

(2)

where \(\rho_0 = n_0 m_p\) and \(\alpha\) is a constant of order of unity. The velocity distribution inside the expanding region \(u(z)\) is nonuniform.

Our extrapolation of this hydrodynamic solution onto the FB is, of course, rather rough. First, the gas distribution in the halo is nonuniform. Second, the analysis does not take into account particle acceleration by the shock. A significant fraction of the shock energy is spent on acceleration that modifies the shock structure. Nevertheless, this model presents a qualitative picture of a shock in the halo.

3.4. Shock Wave Acceleration Phase and Non-Thermal Emission

The theory of particle acceleration by shocks is described in many publications. This theory has been developed, and bulky
numerical calculations have been performed to calculate spectra of particles accelerated by SN shocks and emission produced by accelerated electrons and protons in the range from radio up to TeV gamma rays (see, e.g., Berezhko & Voelk 2010). Nevertheless, many aspects of these processes are still unclear. For instance, the ratio of electrons to protons accelerated by shocks has not been reliably estimated (see Bykov & Uvarov 1999).

We notice that the energy of shock front expected in the GC is nearly two orders of magnitude larger than that of the energy released in an SN explosion. Therefore, the process of particle acceleration in terms of sizes of envelope, number of accelerated particles, maximum energy of accelerated particles, etc., may differ significantly from those observed for SNe. Below we present simple estimations of the electron acceleration by shocks.

The injection spectrum of electrons accelerated in shocks is a power law, \( Q(E) \propto E^{-2} \), and the maximum energy of accelerated electrons can be estimated from a kinetic equation describing their spectrum at the shock (Berezinski et al. 1990), \( E_{\text{max}} \approx v_{\text{sh}} E_{\beta} \), where \( v_{\text{sh}} \sim 10^{8} \text{ cm s}^{-1} \) is the velocity of shock front, \( D \) is the diffusion coefficient at the shock front, and the energy losses of electrons (synchrotron and IC) are \( dE/dt = -\beta E^{2} \). Recall that \( \beta \) is a function of the magnetic and background radiation energy densities, \( \beta \sim w_{\sigma_{T}c}(m_{e}c^{2})^{2} \), where \( \sigma_{T} \) is Thompson cross section and \( w = w_{\text{ph}} + w_{B} \) is the combined energy density of background photons \( w_{\text{ph}} \) and the magnetic energy density \( w_{B} \). It is difficult to estimate the diffusion coefficient near the shock. For qualitative estimation, we can use the Bohm diffusion (\( r_{L}(E_{\gamma}c) \), where \( r_{L} \) is the Larmor radius of electrons. Using the typical values of these parameters, we obtain \( E_{\text{max}} \sim 1 \text{ TeV} v_{8} B_{-5}^{-1/2} w_{-12}^{1/2} \), where \( v_{8} \) is the shock velocity in units of \( 10^{8} \text{ cm s}^{-1} \), \( B_{-5} \) is the magnetic field in the shock in units of \( 10^{-5} \text{ G} \), and \( w_{-12} \) is the energy density in units of \( 10^{-12} \text{ erg cm}^{-3} \).

The spectrum of electrons in the bubble is modified by processes of energy losses and escape. It can be derived from the kinetic equation

\[
\frac{d}{dE} \left( \frac{dE}{dt} N \right) + \frac{N}{T} = Q(E),
\]

where \( dE/dt = \beta E^{2} + \nabla u(z)E \) describes the IC, synchrotron, and adiabatic (because of wind velocity variations) energy losses, \( T \) is the time of particle escape from the bubble, and \( Q(E) = K E^{-2} \theta(E_{\text{max}} - E) \) describes particles’ injection spectrum in the bubble. As one can see, in the general case the spectrum of electrons in the bubble cannot be described by a single power law as assumed by Su et al. (2010). The spectrum of electrons has a break at the energy \( E_{b} \sim 1/\beta T \), where \( T \) is the characteristic time of either the particle escape from the bubble or of the adiabatic losses, e.g., for \( \nabla u = \alpha \) the break position follows from \( T \sim 1/\alpha \). By solving Equation (3), we can see that the electron spectrum above the break cannot be described by a single power law because the cooling timescale \( \tau(E) = 1/\beta E \) is energy dependent.

The distribution of background photons can be derived from GALPROP program. The average energy densities of background photons in the halo are \( u_{\gamma} = 2 \text{ eV cm}^{-3} \) for optical and \( u_{\gamma} = 0.34 \text{ eV cm}^{-3} \) for IR. These background photon energy densities are obviously not negligible in comparison with \( u_{\text{CMB}} = 0.25 \text{ eV cm}^{-3} \) for the relic photons and are also comparable to the magnetic energy density \( (1/2)B_{5}^{2} \text{ eV cm}^{-3} \). The expected IC energy flux of gamma rays and synchrotron radiation emitted from the same population of electrons described above are shown in Figure 1 for different values of \( E_{b} \) and \( E_{\text{max}} \). The Klein–Nishina IC cross section (Blumenthal & Gould 1970) is used. The observed spectrum of radioemission in the range 5–200 GHz and gamma rays are taken from Dobler & Finkbeiner (2008) and Su et al. (2010), respectively. The IC gamma-ray spectrum is formed by scattering on three different components of the background photons. When these three components are combined (see Figure 1(b)), they mimic a photon spectrum \( E^{-2} \) and describe well the data shown in Figure 23 of Su et al. (2010). We want to remark that although a single power law with the spectral indices in between 1.8 and 2.4 in the energy range of electrons from 0.1 to 1000 GeV can also explain both the Fermi data as well as the radio data as suggested by Su et al. (2010), theoretically a more complicated electron spectrum will be developed when the cooling timescale is comparable to the escape time even if electrons are injected with a single power law as shown in Equation (3).

3.5. The Thermal Emission from Heated Plasma

In our model there is 10 keV hot plasma with power \( \dot{W} \sim 3 \times 10^{40} \text{ erg s}^{-1} \) injected into bubbles. Part of these energies is used to accelerate the charged particles in the shock, but a significant fraction of energy will be used to heat up the gas in the halo due to Coulomb collisions. The temperature of halo gas can be estimated as \( \dot{W}d^{3}kT \approx \dot{W}d/v_{\text{w}} \), which gives \( kT \sim 1.5(\dot{W}/3 \times 10^{40} \text{ erg s}^{-1})v_{\text{w}}^{-1}(d/5 \text{ kpc})^{-2}(n/10^{-3}) \text{ keV} \). The thermal radiation power from the heated halo gas is simply given by \( L_{\text{th}} = 1.4 \times 10^{-27}n_{e}n_{i}Z^{2}T^{7/2} \text{ erg cm}^{-3} \) (Rybicki & Lightman 1979). By using \( kT = 1.5 \text{ keV}, n_{e} = n_{i} = 10^{-3} \text{ cm}^{-3} \), and \( Z = 1 \), we find \( L_{\text{th}} \sim 10^{38} \text{ erg s}^{-1} \).
4. DISCUSSION

The observed giant structure of the FB is difficult to explained by other processes. We suggest that periodic star capture processes by the central SMBH can inject $\sim 3 \times 10^{40} \text{erg s}^{-1}$ hot plasma into the galactic halo. The hot gas can expand hydrodynamically and form shock to accelerate electrons to relativistic speed. Synchrotron radiation and IC scattering with the background soft photons produce the observed radio and gamma rays, respectively.

It is interesting to point out that the mean free path of TeV electrons $\lambda \sim \sqrt{D/\beta E_e} \sim 50 D_z^{1/2} t_z^{1/2}$ pc, where $D_z$ and $t_z$ are the diffusion coefficient and cooling time for TeV electrons in units of $10^{28} \text{cm}^2 \text{s}^{-1}$ and $10^5 \text{yr}$, respectively. This estimated mean free path is much shorter than the size of the bubble. In our model the capture time is once every $\sim 3 \times 10^4 \text{yr}$, and we expect that there are nearly about 100 captures in 3 million years. Each of these captures can produce an individual shock front, and therefore, the gamma-ray radiation can be emitted uniformly over the entire bubble.

Furthermore, we can estimate the shape of the bubble if we simplify the geometry of our model as follows. After each capture, a disk-like hot gas will be ejected from the GC. Since the gas pressure in the halo $(n(r)kT \sim 10^{-14}(n/3 \times 10^{-3} \text{ cm}^{-3})(T/3 \times 10^4 \text{ K}) \text{ erg cm}^{-3})$ is low and decreases quadratically for distance larger than 6 kpc (Paczynski 1990), we can assume that the hot gas can freely escape vertically, which is defined as the $z$-direction and hence the $z$-component of the wind velocity $v_{wz} = \text{constant}$ or $z = v_{wz} t$. The ejected disk has a thickness $\Delta z = v_w t_{\text{cap}}$, where $t_{\text{cap}} = 3 \times 10^2 \text{ yr}$ is the capture timescale. On the other hand, the hot gas can also expand laterally and its radius along the direction of the galactic disk is given by $x(t) = v_{wx} t + x_0 \approx v_{wx} t$, where $x_0 \sim 100 \text{ pc}$ (cf. Section 3.2). When the expansion speed is supersonic then the shock front can be formed at the edge of the ejected disk. In the vertical comoving frame of the ejected disk the energy of the disk is $\Delta E$, which is approximately constant if the radiation loss is small. The energy conservation gives $\Delta E = \frac{1}{2}m v_{wx}^2$ with $m = m_0 + m_s(t) = m_0 + \pi x^2 \Delta z \rho$, where $m_0 \approx 2\Delta E/v_{wx}^2$ is the initial mass in the ejected disk, $m_s$ is the swept-up mass from the surrounding gas when the disk is expanding laterally, and $\rho = m_p \rho_0$ is the density of the medium surrounding the bubble. Combining the above equations, we can obtain $\Delta E = \frac{1}{2}m_0 + \pi (v_{wx} t)^2 \Delta z \rho v_{wx}^2$. There are two characteristic stages, i.e., the free expansion stage, in which $v_{wx} \approx \text{constant}$ for $m_0 > m_s(t)$, and the deceleration stage for $m_0 < m_s(t)$. The timescale switching from free expansion to deceleration is given by $m_0 = m_s(t)$ or $t_s = \sqrt{m_0/\pi \Delta z \rho v_{wx}^2}$. In the free expansion stage, we obtain $x = v_{wx} t \sim z$ for $x < v_{wx} t_s = x_s$. In the deceleration stage, $\Delta E \approx \frac{1}{2} \pi (v_{wx} t)^2 \Delta z \rho v_{wx}^2$, we obtain $(x/v_{wx} t) = (\frac{\Delta E}{\pi^2 v_{wx}^2 \Delta z \rho})^{1/3} (\frac{v_{wx} t}{v_{wx} t_s})^{1/2} \approx 0.9 (\frac{x}{v_{wx} t_s})^{1/2}$, we have approximated $v_{wx} \sim v_{wz} \sim v_w \sim 10^8 \text{ cm s}^{-1}$, $\Delta E = 3 \times 10^{52} \text{ erg}$, and $\rho/m_p = 3 \times 10^{-3} \text{ cm}^{-3}$. The switching from a linear relation to the quadratic relation takes place at $z_s \sim v_{wx} t_s \sim 300 \text{ pc}$. The quasi-periodic injection of disks into the halo can form a sharp edge, where shock fronts result from the laterally expanding disks with quadratic shape, i.e., $z \sim x^2$.

In fitting the gamma-ray spectrum it gives $E_\gamma \sim 50 \text{ GeV}$, which corresponds to a characteristic timescale of either adiabatic loss or particle escape of $\sim 15 \text{ Myr}$. By using Equation (2), the characteristic radius of the FB is about 5 kpc, which is quite close to the observed size of the FB.

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