Formation of Fermi Bubbles by Tidal Disruption Events at Galactic Center

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ABSTRACT

Processes of dissipation of energy released during capture and disruption stars by Galactic central Black hole. This process should periodically happen in the Galactic center and affect Galactic center environment as well as Galactic halo. Routine star disruptions by the central supermassive black hole BH provide enough cumulative energy to form the Fermi Bubbles. A single star of super-Eddington eruption provide an subsonic outflow gas whose total energy is about $10^{52}$ erg. The average rate of disruption events is expected to be $10^{-4} - 10^{-5}$yr$^{-1}$ that provides the average power of energy release in the GC $\dot{W} \sim 3 \times 10^{38}$ erg s$^{-1}$, just needed to support Fermi Bubbles in the halo. In the exponential atmosphere the energy from the GC propagates perpendicular to the Galactic plane and provides symmetric features in the halo.

Keywords: ISM: clouds — cosmic rays — gamma rays — radiation mechanisms: non-thermal — MHD turbulence — scattering

1. INTRODUCTION

The origin of enigmatic gamma-ray features of Fermi Bubbles (FBs) in the Galactic central region were found from Fermi-LAT data (see Su et al. 2010; Ackermann et al. 2014). The microwave emission was confirmed later from the excess in Planck data (see Planck Collaboration 2013) whose structures coincided nicely with the Fermi Bubbles. A few mechanisms of gamma-ray and microwave emission from the FBs were interpreted in terms of relativistic electrons by inverse Compton radiation or by hadron collisions. In the first case, high energy electrons in the FBs are produced by in-situ acceleration at the Bubble edges by a shock or by stochastic turbulence nearby (see, e.g., Cheng et al. 2011, 2014, 2015b; Narayanan & Slatyer 2017; Keshet & Gurwich 2017; Mertsch & Petrosian 2018, and references therein). Alternatively, relativistic hadrons are injected from the the Galactic Center (GC), which are then trapped in the halo for timescales $\gtrsim 10^{10}$ yr of the order of the time of p – p collision time (e.g., Crocker & Aharonian 2011; Cheng et al. 2015a; Mou et al. 2015; Yang et al. 2018, and references therein).

The origin of energy release in the GC is still a problem. In general, it is assumed that the initial energy release at the Galactic center (GC) is a result of accretion onto the central supermassive black hole with a mass $\sim 4 \times 10^6 M_{\odot}$, which is identified with the source Sgr A* (see Gillessen et al. 2009). The energy needed to provide this energy release is supposed to be in the range from $10^{53}$ to $10^{56}$ erg s$^{-1}$ (see Bland-Hawthorn & Cohen 2003; Su et al. 2010; Akita et al. 2018; Keshet & Gurwich 2018) when the initial energy release occurred in the GC several million years ago. Miller & Bregman (2016), Keshet & Gurwich (2017) and Akita et al. (2018), assumed that the Bubble boundary was bounded by a shock with an expansion velocity about several hundred km s$^{-1}$ which corresponds to a Mach number about 1.5 $\sim$ 5. Recent UV observations found, indeed, a supersonic outflow with the velocity $\gtrsim 900$ km s$^{-1}$ (see Fox et al. 2015), although, of course, the key process of energy release is still unknown.

At present Sgr A* is quite dim with periodic X-ray flares of a luminosity $10^{35} \sim 10^{36}$ erg s$^{-1}$ (see, e.g., Zhang et al. 2017). However, X-ray emission from the GC molecular clouds indicates that in the past ($\sim$ 100 years ago) there were one or two X-ray flares with the luminosity $10^{39} \sim 10^{41}$ erg s$^{-1}$ (see, e.g., Churazov et al. 2017; Terrier et al. 2018). The duration of flares is estimated as 1 $\sim$ 10 years, which give a total energy release about $10^{48}$ erg. Recent X-ray observations in the direction of the constellation Draco (X-ray source Swift J1644+57) found even more significant energy release,
which was interpreted as a result of tidal disruption of a star by the central black hole. The peak luminosity was detected as $10^{48}$ erg s$^{-1}$ and the total energy release was estimated to be $3 \times 10^{53}$ erg (Burrows et al. 2011). Another example of huge energy release was presented in Donato et al. (2014) who interpreted a flare in the Abell cluster 1795 as a disruption energy release about $1.7 \times 10^{52}$ erg by a black hole with a mass about $3 \times 10^6 M_\odot$.

2. HYDRODYNAMICAL SIMULATIONS OF THE GAS OUTFLOW FROM SGR A* IN THE PAST(?) MODELS FOR GAS OUTFLOW FROM SGR A* (?)

Several models of giant Fermi Bubbles were analysed as a gas outflow from Sgr A* when huge energy was released in the Galactic centre. One of the scenarios was suggested by Zubovas et al. (2011); Zubovas & Nayakshin (2012) (see also Nayakshin & Zubovas 2018). A giant molecular cloud of mass $\sim 10^5 M_\odot$ was captured by the central black hole $\sim 10^6$ yr ago. An almost spherical outflow from Sgr A* was caused by a relatively short single burst of AGN activity when a very bright quasar phase was coincided with a past event. It is unlikely that the jets are completely uncorrected with the expected large-scale structure from the central black hole (Guo & Mathews 2011). In contrast, Zubovas et al. (2011) assumed a symmetrical pair of lobes of an outflow from near the black hole.

The outflow is estimated to have a solid angle $\sim \pi$, and speed $v \sim 0.1c$. The wind flow propagates with a constant velocity $v$ until it penetrates into the interstellar gas by sweeping into a shock shell, and the outflow drives in directions away from the plane. The central molecular zone (CMZ) presents an almost impossible barrier to the Sgr A* outflow in other directions. The kinetic energy of outflow is estimated as

$$E_{\text{lobes}} \sim \frac{v^2}{2} \Delta M \sim 4 \times 10^{55} \text{erg},$$

where the matter, expelled into the lobes from the hole, is $\Delta M \sim 4 \times 10^3 M_\odot$.

The bubble continues to expand, when the activity of black hole (energy release) has been switched off at $t > 1$ Myr but the flux of gas is expanding perpendicular to the bubble surface. The evolution of the hot bubbles is driven by the inertia of the outflow. The density of the background gas outside the bubbles is constant, while the density inside the bubbles is less dense than the background and is a function of coordinates and time (but the pressure inside is higher than outside).

Mou et al. (2014) suggested an alternative scenario, when the mass accretion rate of hot flow in Sgr A* was $10^3 \sim 10^4$ times higher than present. Its activity lasted for $10^7$ yr and ceased about $0.2 \times 10^6$ yr ago. The required power of the wind during the period of past activity is $\sim 2 \times 10^{41}$ erg s$^{-1}$. Similar analysis of Weaver et al (1977) for a star was investigated with a constant mechanical luminosity $L_w$ and a terminal velocity $v_w$ at time $t > 0$ in a background gas. The flow is propagating into the uniform ISM distribution when the un-shocked ISM gas is adjoined with a shocked wind (Mou et al. 2014). In the inner region, the massive CMZ gas acts like a wall around Sgr A*, preventing the wind flowing in the horizontal direction. The winds collide with the CMZ and the kinetic energy of winds is converted into thermal energy. The high pressure gas escapes towards the polar directions.

Unlike other models, we assume that the energy release in Sgr A* to form the Fermi Bubbles is produced by routine star disruptions by the central black hole (see Cheng et al. 2011, 2012). This idea of releasing $\sim 10^{52}$ erg in GC was suggested in Rees (1988); Cheng et al. (2006, 2007). In the close vicinity of Sgr A (less than 0.04 pc from it) there are about 35 low-mass stars ($1 \sim 3 M_\odot$) and about 10 massive stars ($3 \sim 15 M_\odot$) (see, e.g., Alexander & Livio 2004; Genzel et al. 2010). The expected energy release produced by accretion processes in the GC may be $\geq 10^{52}$ erg depending on the mass of the captured stars (Dai et al. 2018). The expected frequency of stellar capture equals roughly $\nu_c \sim 10^{-4} \sim 10^{-5}$ yr$^{-1}$ (see the review of Alexander 2005). The outflow of the gas from Sgr A* is propagating in the stratified gas of the halo. Below we develop the model based on hydrodynamical simulations of the stationary model when low-mass stars supply energy in the GC.

3. PLASMA OUTFLOW GENERATED BY PROCESSES OF STAR DISRUPTION AND APPEARANCE OF SHOCK

Routine processes of star disruption by the supermassive black hole in GC provide enough energy to the halo to form FBs. X-ray observations of jetted tidal disruption event Sw 1644 (Kara et al. 2016) can be interpreted as fast outflows from super-Eddington accretion. Dai et al. (2018) analysed super-Eddington accretion of a disrupted star through simulation. They showed that the accretion energy is mainly carried away by the following channels: (1) radiation with efficiency of about $\eta_{\text{rad}} \approx 3\%$, (2) jet with $\eta_{\text{jet}} \approx 20\%$, and (3) outflow with $\eta_{\text{of}} \approx 20\%$ (where $\eta$ is the ratio to $M c^2$). Also, the outflow has a speed of several tenths of $c$ from most inclination angles. The specific values of the efficiencies and the outflow speed depend on parameters such as the mass and spin of the black hole, the accretion rate. However, most of the current simulations of super-Eddington accretion with parameter settings gave consistent results (e.g., Jiang et al. 2014; Sadowski & Narayan 2016). Therefore, we adopt that in all tidal disruption events (TDEs), outflows with speed of several tenths of $c$ are produced, and they carry away up to 10% of the accretion energy. Such fast outflows
provide the most impact on the surrounding matter since they carry away a lot of matter moving with non-relativistic velocity. Also, it is likely that only a small fraction of tidal disruption events can produce jets.

Given the average mass of outbound matter approximately $0.5M_\odot$ for a TDE of a solar mass star, one can estimate the total energy of the outflow as $10^{52} \sim 10^{53}$ erg in the case of disruption of a solar-mass star. With these input parameters (outflow velocity $v_0 \approx 0.1c \sim 0.3c$, total energy $W \approx 10^{52} \sim 10^{53}$ erg) we intend to search evolution of these fluxes in the surrounding medium of the black hole. In terms of total efficiency, it accounts for up to $1 \sim 10\%$ of the total rest mass energy of the disrupted star. The rate of the average tidal disruption events can reach the value of $10^{-4}$ yr$^{-1}$ (Syer & Ulmer 1999), and therefore, the total power can be as high as $W \leq 3 \times 10^{41}$ erg s$^{-1}$.

Very recently, using XMM and Chandra, Ponti et al. (2019) discovered two X-ray chimneys extended above and below the GC on scales about hundred pc. Nearby Sgr A* observations showed $\pm 15$ pc bipolar lobes filled with plasma at temperature about 1 keV. Taking into account of the gas pressure and the gravitational potential in the GC, this generates an outflow with the velocity around 500 km s$^{-1}$ from the central region. The observations found more extended emissions above the lobes of 15 pc, which are seen as “chimneys”. They are seen at a distance 160 pc above the Galactic plane. Their thermal energy is about $3 \times 10^{52}$ erg. The chimneys are confined along the longitudinal directions of cylindrical shape with sharp edges. It is reasonably to assume that the emission from the lobes and chimneys may be a result of recent event of energy injection from the GC. The new X-ray observations can be interpreted as the result of a recent event of star capture by the central black hole.

4. ANALYTICAL SOLUTION FOR SHOCK PROPAGATION IN THE EXPONENTIAL ATMOSPHERE OF THE GALACTIC HALO

The expected energy from a TDE by the GC central black hole is estimated to be $10^{52} \sim 10^{53}$ erg (Dai et al. 2018). The energy freely escapes in the form of following outflow/shock in the halo. The plasma density in the Galactic halo drops exponentially with the altitude $z$ above the Galactic plane (see, e.g., Cordes et al. 1991, for the latest results of gas distribution in the Galaxy see Biswas & Gupta 2018)

$$n(z) = n_0 \exp \left( -\frac{z}{H} \right),$$

where $n_0$ is the gas density above the plane and $H$ is the characteristic scale of density variations. Nordgren et al. (1992) estimated the density of free electrons above the plane as $n_0 = 0.033$ cm$^{-3}$ and the characteristic scale of electron distribution there as $H = 0.53 \sim 0.84$ kpc.

Kompaneets (1960) developed the formalism of explosion with a shock front propagates through an exponential atmosphere, and its volume is expanding with time. An analytical solution of hydrodynamic model for a shock wave propagation in the exponential atmosphere was developed later by Baumgartner & Breitschwerdt (2013) (see also the review of Bisnovatyi-Kogan & Silich 1995).

These solution for the Fermi Bubbles was applied by Cheng et al. (2012) for the exponential atmosphere in the Galactic halo, which is presented in terms of the variable $y$ (as a new time variable)

$$y = \int_0^t \sqrt{\frac{(\gamma - 1)}{2}} \frac{2W(t)}{3n_0 V(t)} dt,$$

where $n_0 = n_0 m_p$, and $W$ is the energy released by a central source. The bubble lateral radius $r(z, t)$ at the altitude $z$ ($z > 0$) is

$$r(z, t) = 2H \cos^{-1} \left[ \frac{1}{2\sqrt{R}} \left( 1 - \frac{y^2}{4H^2} + R \right) \right],$$

where $R = \exp(z/H)$, and the bubble volume $V(t)$ is presented as

$$V(t) = \pi \int_0^z r^2(z, t) dz.$$  

With the normalized variables

$$\tilde{V} = \frac{V}{H^3}, \quad \tilde{y} = \frac{y}{H},$$

the velocity of the shock at the bubble’s top is

$$\frac{d z_u}{d t} = \frac{\beta}{t_{SN}} \cdot \left( \frac{H}{1 - \tilde{y}/2} \right) \cdot \frac{1}{\sqrt{\tilde{V}(\tilde{y})}},$$

where $\beta = 5/3$, $\rho_0$ is the gas density, $E_{th}$ is the thermal energy of the gas and $t_{SN} = \sqrt{\rho_0 H^5 / E_{th}}$ and $z_u$ is the position of the bubble’s top which is a function of time,

$$z_u = -2H \ln(1 - \tilde{y}/2).$$

In the stationary situation the bubble structure reaches the lateral radius of side boundary $r \approx \pi H$ (see Eq. (4), and the top position of the bubble at $z_u \to \infty$. The stationary structure is similar to a cylinder of side as shown in Fig. 1.

Transformation of the bubble-bubbles structure can be presented by $t$ as (e.g. for a stationary energy release, $W(t) = 5/11L_w t$) In fact, the time $t$ can be presented explicitly in terms of $\tilde{y}$ (e.g., for a steady energy release, $W(t) = 5/11L_w t$)

$$t(\tilde{y}) = \frac{L_0^{1/3} H^{5/3}}{L_{w0}^{1/3}} \left( \frac{22}{15^3} \int_0^{\tilde{y}} \sqrt{\tilde{V}(\tilde{y})} d\tilde{y} \right)^{2/3}. $$
Figure 1. Structure of the bubble for capture events of tidal disruptions which is evaluated permanently to a cylinder of a limit radius.

5. SINGLE AND MULTIPLE DISRUPTION EVENTS

As it follows from this solution at \( t > 0 \) within the altitude \( z \leq H \), the velocity of the Sedov solution is initially presented by a decreased velocity of shock envelope with \( z \). Following the discussion in section 4, the velocity of the shock envelope is decreasing when altitude \( z \leq H \ (t > 0) \). At altitudes \( z > H \) a shock propagates in the exponential atmosphere afterwards with acceleration. The position of velocity minimum \( \tilde{y} = \tilde{y}_{\text{acc}} \) is determined by the condition \( \frac{\ddot{z}}{z} = 0 \). The acceleration at the top is \(^{1}\)

\[
\frac{\ddot{z}}{z} = \frac{H}{t_{\text{SN}}^2} \frac{\beta^2}{2(1 - \tilde{y}/2)} \left( \frac{1}{V(\tilde{y})} - \frac{1}{V(\tilde{y})} \frac{dV(\tilde{y})}{d\tilde{y}} \right)
\]

(see Baumgartner & Breitschwerdt 2013, for details).

If the shock velocity at any \( z \) drops below the sound velocity \( c_s \), then it is absorbed in the halo inside there. Otherwise, a shock is able to penetrate into the halo with a velocity higher than the sound speed \( c_s \) and transfers the energy of the initial central source into the exponential atmosphere. Baumgartner & Breitschwerdt (2013) defined the condition of shock penetration into the exponential atmosphere when the velocity of shock front is higher than \( c_s \), \( \tilde{z}_{\text{acc}}(\tilde{y}_{\text{acc}}) > 3c_s \).

For illustration purpose we show in Fig. 2 the velocity distribution for the case \( H = 0.5 \) kpc and \( n_0 = 0.03 \) cm\(^{-3} \), and \( W = 3 \times 10^{54} \) erg (solid line) and \( W = 10^{53} \) erg (dashed line). The dotted line shows the level \( 3c_s \) in the halo \( 3 \times 10^7 \) cm s\(^{-1} \).

\(^1\) There are misprints in Eqs. (B.2) and (B.3) for the shock acceleration presented in Baumgartner & Breitschwerdt (2013).

Figure 2. Temporal variations of the shock velocity of the bubble’s top in the halo: \( W = 3 \times 10^{54} \) erg (solid line) and \( W = 10^{53} \) erg (dashed line). The dotted line denotes three times the sound velocity in the halo \( 3 \times 10^7 \) cm s\(^{-1} \).

For a single source the energy occupies more and more volume of the exponential atmosphere at \( t > 0 \), eventually reaching a top infinitely. In the end, the structure of a single source disappears as the energy it releases is distributed over an infinite volume.

For the parameters in the GC a single star disruption is unable to provide energy enough for the Fermi Bubbles, i.e., no more than \( 10^{52} \sim 10^{53} \) erg (Dai et al. 2018). Our calculations show that an unbelievably single star event with an energy \( W = 3 \times 10^{54} \) erg is needed to penetrate the outflow into the halo.

Alternatively this energy can be supplied as a cumulation of several disruptions of weaker events with the permanent luminosity \( L_w \). It follows from Dai et al. (2018) any event of star disrupter provides energy of \( 10^{52} \sim 10^{53} \) erg with the average frequency star capture is about \( 10^{-4} \) yr\(^{-1} \). In the end, the structure of a cumulative explosions comes to a stationary situation of the bubbles. The energy flux of the central source escape permanently to infinity. In Fig. 3 we show temporal velocity variations for different values of \( L_w \) in the initial development of the structure in the halo. We show that the velocity of the envelope exceeds the sound speed if \( L_w \geq 10^{40} \) erg s\(^{-1} \).

6. PARTICLE ACCELERATION AT BUBBLE EDGES

Different processes of cosmic ray (CR) acceleration are expected at the borders of the bubbles connected with peculiarities of the bubble hydrodynamics. A detail analysis is out of the scope of the present discussion. Although its analysis is not a topic of our investigations. Evidently, CRs are accelerated in the Fermi Bubbles, and nonthermal emissions from there are observed in gamma-ray (see, e.g., Su et al. 2010; Ackermann et al. 2014) and microwave (see Planck Collaboration 2013).
The spatial distribution of the emissions shows sharp edges of the Bubbles. These characteristics of emission can be interpreted in terms of relativistic electrons, which may fill a thin envelope of the Bubble because of the relatively short lifetime there.

The standard scenario of shock acceleration was applied for the interpretation of the Bubble (e.g., in Cheng et al. 2011), whose emission in the envelope is generated by relativistic electrons (see, e.g., electron distribution in a shell presented by Bulanov & Dogel 1979).

Alternatively, model of stochastic Fermi II acceleration (Fermi 1949) is assumed behind the shells of Fermi Bubbles. This model was derived from analytical linear treatments by Mertsch & Sarkar (2011); Mertsch & Petrosian (2018) when MHD-instabilities are excited there. Nonlinear model of stochastic acceleration in plasmas was presented in Chernyshov et al. (2012), as well as related problems of stochastic acceleration could be found in Cheng et al. (2014, 2015b).

The stochastic acceleration is expected in regions of the shell where instabilities are generated there, e.g., by the Rayleigh-Taylor (see Chandrasekhar 1961). This hydrodynamic turbulence is expected at the top of the shell of the Fermi Bubbles, where the velocity of gas is high enough and its positive acceleration, \( \ddot{\rho}(z) > 0 \), is effective for short time, \( \tau_{\text{rti}} \), for Rayleigh-Taylor instability (see Baumgartner & Breitschwerdt 2013).

\[
\tau_{\text{rti}} = \frac{\Delta d(\tilde{y})}{2\pi \rho_a(\tilde{y})} \left( \frac{\rho_{\text{sh}} + \rho_{\text{in}}}{\rho_{\text{sh}} - \rho_{\text{in}}} \right),
\]

where \( \rho_{\text{sh}} \) and \( \rho_{\text{in}} \) are the plasma density be from and inside the envelope, \( \rho_{\text{sh}} = 4\rho_0 \exp[-z_a(\tilde{y})/H] \) is the plasma density at the shock and \( \rho_{\text{in}} = M_{\text{ej}}(\tilde{y})/V_{\text{in}}(\tilde{y}) \), and \( \Delta d(\tilde{y}) \) is the thickness of the shell. Here \( M_{\text{ej}} \) is the mass ejected by the central source (source wind), \( V_{\text{n}} \) is the volume filled with the wind plasma, which is an ellipsoid with semi-axes \( a_{\text{in}}(\tilde{y}) = a(\tilde{y}) - \Delta d(\tilde{y}) \) and \( b_{\text{in}}(\tilde{y}) = b(\tilde{y}) - \Delta d(\tilde{y}) \). The shell thickness is determined as

\[
\Delta d(\tilde{y}) = \frac{\int_0^z \rho(z) dV}{\int_0^z \rho_{\text{sh}}(\tilde{y}) dA_f(\tilde{y})}.
\]

Here \( V \) and \( A_f \) are the volume and the surface of the ellipsoid.

Baumgartner & Breitschwerdt (2013) defined the lifetime of the shock against the Rayleigh-Taylor instability from the condition

\[
\tau_{\text{rti}} = \tau_{\text{dyn}},
\]

where

\[
\tau_{\text{dyn}} \approx \frac{a(\tilde{y})}{z_a(\tilde{y})},
\]

when \( \tau_{\text{dyn}} > \tau_{\text{rti}} \), instabilities are expected at the top of the Fermi Bubbles.

For energy release \( L_w \approx 3 \times 10^{40} \text{ erg s}^{-1} \) the instability is excited at height of about 3 kpc, (see Cheng et al. 2015b). The acceleration of electrons ceases, when the time of stochastic acceleration, \( \tau_{\text{acc}} \), is longer than the characteristic time of their confinement is the turbulence region, \( \tau_{\text{dyn}} \), i.e. when

\[
\tau_{\text{acc}} \geq \tau_{\text{dyn}}.
\]

For the Fermi bubbles, the position high-energy cutoff in the spectrum of accelerated electrons is determined from the balance between acceleration and escape (see Cheng et al. 2015b) and the time of acceleration there is \( \tau_{\text{acc}} \approx 5 \times 10^{12} \text{ s} \). The regions of strong turbulence are expected in the Galactic Halo of several kpc above the disk, where accelerated electrons may generate the observed emission of the Fermi bubbles in gamma and microwave energy ranges.

Another mechanism of CR acceleration can occur in a uniform flux of the gas with a velocity shear (Berezhko & Krymskii 1981; Earl et al. 1988, see also step-function shear flows in Jokipii & Morfill 1990 and Webb et al. 2018). This mechanism is similar to a stochastic Fermi acceleration but with a large scale shear of regular velocity structure. Similar acceleration may be expected in outflow of plasma in the Fermi Bubble. This mechanism is similar to stochastic Fermi II acceleration with the turbulent effect replaced by the large scale shear of the flow. As shown in Fig. 5, for the case of multiple TDEs there are large scale shear flows (eddies) in the Fermi Bubbles.

We mention also the model of the Fermi bubbles generated by hadrons of nonthermal emission in the halo.
(Crocker & Aharonian 2011). However, this hadron restricted by permitted free parameters of this mechanism (e.g., Cheng et al. 2015a, and references therein Mou et al. 2015; Yang et al. 2018). We mention also the model of Fermi Bubbles formed by nonthermal emission by energetic hadrons in the halo (Crocker & Aharonian 2011). However, this model is limited by the unrealistic value of parameters required to fit the data (e.g., Cheng et al. 2015a, and also Mou et al. 2015; Yang et al. 2018).

7. NUMERICAL RESULTS

Numerical simulations are provided for the model of stationary routine of star disruptions in the GC. Analytical calculations developed a model of stationary structure of the Bubbles similar to a vertical cylinder whose parameters are depended on the stationary luminosity in the central source in the GC. Similar analysis of Weaver et al (1977) for a star was investigated when a central source is characterized by a stationary luminosity $L_0$ and a strong wind of a star interacts with the uniform interstellar medium which is swept-up at the border of the wind as a relatively thin dense shell. The flow is propagating into the uniform ISM distribution when the un-shocked ISM gas is adjoined with a shocked wind. The inner apart of the shell is adjacent to the shocked stellar wind of low density and hot plasma.

We perform hydrodynamic simulations of the formation of the Bubbles by (sequential) multiple TDEs at the GC. We adopted the publicly available MHD simulation package FLASH. The Galactic halo is modelled as a layered exponential atmosphere of characteristic scale (i.e., scale height) 1 kpc. The density and pressure at the mid-plane are taken as $1.24 \times 10^{-26}$ g cm$^{-3}$ and $10^{-12}$ erg cm$^{-12}$, respectively. Each TDE is represented by a fixed amount of energy released in a small volume at the centre (200 pc in radius).

As an example, we considered the case that each TDE releases $10^{53}$ erg and the interval between successive TDEs is 0.01 Myr. We run the simulation for 7.5 Myr. The results are shown in the left panels of Figs. 4 & 5. For comparison we also simulate the case of a single TDE. We take the energy release of this TDE as $7.5 \times 10^{55}$ erg, which is the total energy release of the case of multiple TDEs at the end of simulation, i.e., 7.5 Myr. However, in this case, the bubble is of comparable size for 4 Myr only, see right panels of Figs. 4 & 5.

There are a couple of points worth mentioning when comparing the two cases. The interior of the case of multiple TDEs has a lot of shocks and more turbulent. There are eddies near the lateral edge of the bubbles in the case of multiple events, while none for the case of single event. The expansion rate of the case of single event is higher than the case of multiple events.

8. CONCLUSIONS

![Figure 4. Density distribution of Fermi Bubbles simulation. Left: Multiple TDEs with each TDE releases $10^{53}$ erg of energy and the interval between successive TDEs is 0.01 Myr. Right: Single TDE with energy release $7.5 \times 10^{55}$ erg.](image)

![Figure 5. Velocity distribution of Fermi Bubbles simulation. Parameters same as Fig. 4. Left: Multiple TDEs. Right: Single TDE.](image)

We briefly analyzed the processes of dissipation of energy released during the capture and disruption of stars by the supermassive black hole at GC. These processes should periodically happen in the GC and should affect the ambient environment of the GC as well as the Galactic halo. Our conclusions can be summarized in the following way:

- We supposed that cumulative processes of routine star disruptions by the supermassive black hole at the GC provide enough energy create the Fermi Bubbles in the halo.
- Numerical simulations of super-Eddington acceleration gave the parameters of single disruption of a solar mass star in the close vicinity of the GC (Dai et al. 2018). During tidal disruption events, outflows of gas with a speed of several tenths of $c$ are produced. They carried away about 10% of the accretion energy into the surrounding medium. The total energy of the outflow is about $10^{52} \sim 10^{53}$ erg.
- Using recent X-ray observations, Ponti et al. (2019) found bipolar chimneys at a distance of
150 pc from the GC. It can be assumed that this emission from chimneys may be a result of recent event of energy injection from the GC.

The thermal energy of the chimneys is about \(4 \times 10^{52}\) erg which is compatible with the simulations by Dai et al. (2018).

- The average rate star tidal disruption events in the GC is expected to be \(10^{-4} \sim 10^{-3}\) yr\(^{-1}\) (Syer & Ulmer 1999; Alexander 2005). Then the average power release is about \(W \sim 3 \times 10^{41}\) erg s\(^{-1}\) provided by the routine process of star disruption in our Galaxy.

- The energy release from the GC into the halo propagates through the exponential atmosphere mainly in the directions perpendicular to the Galactic Plane. In these conditions the energy required to penetrate through the halo by one single energy release is about \(\sim 10^{55}\) erg. On the other hand, for single energy release of a star disruption is about \(10^{52} \sim 10^{53}\) which will disappear into the local vicinity.

- For multiple capture of star events at the GC, the cumulative energy release can supply the energy needed for the Fermi Bubbles in the halo. The luminosity required for this case is about \(\gtrsim 10^{41}\) erg s\(^{-1}\). Unlike a single event that is bound to disappear with time, these routine star disruptions may generate a stationary structure similar to a vertical cylinder restricted by side shells and the energy flux propagates steadily through it.

- We perform hydrodynamic simulations of the formation of the Bubbles via (sequential) multiple TDEs at the GC. We modelled the halo as a layered exponential atmosphere of scale height 1 kpc.

Each TDE is represented by a fixed amount of energy released in a small volume enclosing the centre (200 pc in radius). We adopted the MHD simulation package FLASH. As an example, we considered the case that each TDE releases \(10^{53}\) erg and the interval between TDEs is 0.01 Myr. The simulation is run for 7.5 Myr and the total energy release at the of the simulation is \(7.5 \times 10^{55}\) erg. For comparison we also run the case of a single TDE with same total energy release \(7.5 \times 10^{55}\) erg.

- When the case of multiple TDEs and the case of single TDE are compared, we found that (1) the interior of the multiple events is far more turbulent and has plenty more shocks. (2) There are eddies (shear flows) near the lateral edge of the bubbles in the case of multiple events, while none for the case of single event. This may be conducive to CR acceleration via the so called CR viscosity.

- Although the situation is not stationary yet, there is a tendency for a cylindrical structure with vertical flow inside the bubbles parallel to the bubble boundary.

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Software: package FLASH

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