Alternative Models of the Fermi Bubbles

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- Parameters of gamma ray and radio emission from the Bubbles.
- General notes about the emission origin.
- Stochastic acceleration from background plasma.
- Problems and solutions.
- Stochastic re-acceleration of electrons injected by SNRs.
- Hadronic model of the Bubbles. Problems of the pure hadronic interpretation of the gamma ray and microwave emission from the Bubbles
- Conclusion
When the diffuse Galactic component is subtracted

\[ \text{FERMI data} - \text{Gas (}\pi^0 + \text{bremsstrahlung}) = \]
Radio Lobes of Polarized Radio Emission at \( v = 2.3 \) GHz (Carretti et al. 2013)

WMAP PI + magnetic angle

Galactic Centre Spur
Northern Ridge
NW limb brightening
SW limb brightening
NE limb brightening?
Southern Ridge
Bubbles from Planck data


The morphology similarity and correlation between GHz and gamma-ray GeV luminosities implies that the bubbles are real and their multi-wavelength emissions have common origin. The existence of such "haze" implies a population of anomalously hard spectrum electrons toward the GC.
Characteristics of the Bubbles: Sharp edges and hard gamma spectrum

Bubbles show energetic spectrum and sharp edges.
Spectrum and Spatial Distribution of Gamma-Ray Emission from the Bubble (Su et al. 2010)

Sharp Edges
Galactic haze with Planck

Ade et al., A&A 554, 139 (2013)

haze spectrum is harder than ambient
Characteristics of nonthermal emission from the Fermi bubbles

• Gamma-rays
  Flux in the range 1 - 100 GeV,
  Spectrum
  Cut-off at
  \[ F_\gamma \sim 4 \times 10^{37} \text{ erg/s} \]
  \[ \propto E_\gamma^{-2.1} \]
  \[ E_\gamma \sim 100 \text{ GeV} \]

• Microwave radiation
  Flux in the range 23 - 61 GHz,
  Spectrum
  \[ \Phi_r \sim (1 - 5) \times 10^{36} \text{ erg/s} \]
  \[ \propto \nu^{-0.56} \]
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## Origin of the Bubble gamma-ray emission

<table>
<thead>
<tr>
<th>Hadronic</th>
<th>Leptonic</th>
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<tbody>
<tr>
<td>( p + p \rightarrow 2\gamma + e^\pm )</td>
<td>( \text{IC: } e + \gamma \rightarrow \gamma' + e' )</td>
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<tr>
<td>- Lifetime in the Bubbles ( \sim 10^{10} ) yr. Can be produced anywhere in the Galaxy.</td>
<td>- Are confined in the Galaxy (&lt; 1 Myr)</td>
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<tr>
<td>- But how to confine them in the Bubbles?</td>
<td>- Should be produced in-situ</td>
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<td>- Spectrum of secondary electrons is steeper than follows from the Planck data</td>
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| A) Crocker & Aharonian, 2011 | A) Su et al., 2010 |
| Crocker et al., 2014, Yang et al., 2014 | Starburst или jet \( \rightarrow \) giant shock from \( 10^{56} \) erg energy release |
| 1) 0.04 SN/cen inside 1.5° of the GC => \( 10^{40} \) erg/s \( (F_\gamma \sim 4 \times 10^{37} \) erg/s) | B) Guo & Mathews, 2011; Yang et al., 2012 |
| 2) "magnetic walls" (Jones et al 2012) | Jet – electron propagation (almost) without scattering |
| C) Thoudam (2013) – injection + compression | Stochastic Acceleration (Fermi II) |
| E) Cheng et al., 2011 | E) Cheng et al., 2011 |
| Star captures \( \rightarrow \) shock wave acceleration | |
Source – energy release in or nearby Sgr A*?

- Hypothetical single capture of a very massive object (molecular cloud?) - $M \sim 10^5 M_\odot$, energy release $W \sim 10^{56}$ erg (e.g. Guo et al. 2012; Zubovas & Nayakshin 2012 and many others)
- Supernova explosions in the GC, power $W \sim 10^{40}$ erg/s (Crocker & Aharonian 2011)
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Main idea from Fermi (1949, 1954) - different frequency of collisions with head-on and following collisions \((v \gg u)\)

Relative velocity

Frequency of collisions with head-on and following clouds

\[ \nu \approx n_d \sigma (v \pm u) \]

\[ \Delta \nu \approx 2n_d \sigma u \]

The rate of energy increase

\[ \frac{dE}{dt} \sim \Delta \nu \times \Delta E = 2\sigma n_d v \frac{u^2}{v^2}E = \alpha E \]
Model of stochastic acceleration of electrons in the Bubbles (Mertsch & Sarkar, 2011)

- From the ROSAT data of Snowden et al. (1997) - a shock front t at the bubble edge with the velocity ≤ 1000 km/s, the total energy estimated from parameters of the hot plasma in the Bubbles ~10^{54-55} erg, the age ~10^7 yr;
- Plasma instabilities, in particular Rayleigh-Taylor and Kelvin-Helmholtz instabilities, would then generate turbulence at the outer shock as in SNR envelopes (from Yang and Liu, 2013)

![Image of turbulence](image)

- The instabilities are convected into the bubble interior by the downstream plasma flow;
- Then the equation is

\[
\frac{\partial f}{\partial t} - \frac{\partial}{\partial p} \left( p^2 D_{pp} \frac{\partial}{\partial p} \frac{f}{p^2} \right) - \frac{f}{t_{esc}} + \frac{\partial}{\partial p} \left( \frac{dp}{dt} f \right) = 0
\]
\[ n(p) \propto \begin{cases} \ p^{-\sigma} & p < p_0 \\ p^2 \exp\left(-\frac{p}{p_0}\right) & p > p_0 \end{cases} \]

\[ \sigma = -\frac{1}{2} + \sqrt{\frac{9}{2} + \frac{t_{acc}}{t_{esc}}} \]

**FIG. 1.** Relevant timescales (top) and the electron spectrum (bottom), at various distances \( x = \xi L \) from the shock.
Spatial distribution of gamma-ray emission in the Bubbles.
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Region of turbulent magnetic fields in the halo behind a shock front
The Model of Stochastic Acceleration

• Two cases:
• a) Acceleration from background plasma;
• b) Re-Acceleration of Relativistic Electrons emitted by SNRs

Equations

\[ \frac{\partial f}{\partial t} + \frac{1}{p^2} \frac{\partial}{\partial p} p^2 \left[ \left( \frac{dp}{dt} \right)_C f - \{ D_C + D_F(p) \} \frac{\partial f}{\partial p} \right] = 0 \]

\[ -\nabla D(r, z, p) \nabla f + \frac{1}{p^2} \frac{\partial}{\partial p} p^2 \left[ \frac{dp}{dt} f - \kappa(r, z, p) \frac{\partial f}{\partial p} \right] = Q(p, r) \delta(z) \]
Spectrum of CRs accelerated by a shock from a background plasma (Vladimirov et al. 2006)
The question is how correctly estimate the number of particles accelerated from background plasma

\[
\frac{dE}{dt}_i = -\frac{2\pi ne^4}{m_e\sqrt{E}} \Lambda
\]

\[
\left(\frac{dE}{dt}\right)_F = \alpha E
\]

\[
\frac{dE}{dt}_i = \left(\frac{dE}{dt}\right)_F \rightarrow E_{thr}
\]

Number of accelerated particles

\[
N_{nth} \sim \exp \left( -\frac{E_{thr}}{kT} \right)
\]

Figure 21.2. Comparison of the acceleration rate and energy loss rate due to ionisation losses for a high energy particle.

• The question is how correctly estimate the number of particles accelerated from background plasma
Spectrum of thermal and nonthermal particles

Equilibrium Maxwellian spectrum

\[ \frac{1}{p^2} \frac{\partial}{\partial p} \frac{p^2}{\partial f} \left\{ \frac{v_0}{p^2} f - \left( \frac{v_0}{p^3} \frac{T}{m} \right) \frac{\partial f}{\partial p} \right\} = 0 \]

Power-law spectrum of accelerated electrons

\[ \frac{\partial f}{\partial t} + \frac{1}{p^2} \frac{\partial}{\partial p} p^2 \left\{ \left[ \frac{dp}{dt} \right]_{\text{loss}} \right\} f - (\alpha(p)) \frac{\partial f}{\partial p} = 0 \]

Wrong estimate!
Spectrum of particles in the case of acceleration from a background plasma (Gurevich 1960)

\[
\frac{\partial f}{\partial t} + \frac{1}{p^2} \frac{\partial}{\partial p} p^2 \left[ \left( \frac{dp}{dt} \right)_C f - \left\{ D_C + D_F(p) \right\} \frac{\partial f}{\partial p} \right] = 0
\]
Acceleration from background plasma for the case when \( T = \Phi(f) \neq \text{const} \)

- **Wolfe & Melia (2006) and Petrosian & East (2008):** The energy gained by the particles is distributed to the whole plasma on a timescale much shorter than that of the acceleration process itself. Because of the relatively inefficiency of bremsstrahlung for cooling the accelerated electrons, this tail is quickly dumped into the thermal body of the background plasma (plasma overheating without a prominent tail of accelerated particles).

- **Chernyshov, Dogiel & Ko (2012):** For a high value of the acceleration momentum \( p_0 \) the run-away flux of thermal particles cools the plasma down from the very beginning. In spite of energy supply by external sources the plasma temperature drops down (analogue to Maxwell demon). Acceleration with a prominent tail of accelerated particles.

\[
D(p) = D_o \rho^\epsilon \theta(p - p_0)
\]

- The regime of acceleration depends strongly on \( p_0 \)
Maxwell demon

System at Equilibrium

The Demon and the friction-free trap door

System with Lower Entropy (in violation of the Second Law)
Spectrum of thermal and nonthermal particles (below from Chernyshov et al. 2012 and Cheng et al. 2014)
Wave Absorption by CRs

- Equation for the spectrum of MHD fluctuation for the Krachann spectrum of turbulence (Normann & Ferrara 1996)
  \[
  \frac{d}{dk} \left[ C \left( \frac{k^{3/2} W(k)}{\rho V_A} \right)^{3/2} \right] = -2 \Gamma_{cr} W + \Phi \delta(k - k_0)
  \]

- Wave absorption increment
  \[
  \Gamma_{cr} = \frac{\pi Z^2 e^2 V_A^2}{2 kc^2} \int_{p_{res}}^{\infty} \frac{dp}{p} F(p)
  \]

- Coefficient of momentum diffusion (stochastic acceleration)
  \[
  D(p) = p^2 \frac{12 \pi V_A^2 k_{res} W(k_{res})}{v r_L B^2}
  \]

From Cheng et al. 2014
a) Spectrum of particles accelerated from a background plasma
b) Time of plasma heating vs time of particle acceleration
Parameters of the model of stochastic acceleration

- Acceleration time $\tau \sim 3 \times 10^6$ yrs, source power $W \sim 5 \times 10^{39}$ erg/s, but (!) $p_0 \sim 0.34$ mc
- A very precise parameter of acceleration $p_0$ is needed to reproduce the gamma-ray spectrum from the Bubble if electron are stochastically accelerated from the background plasma.
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Equation for electron re-acceleration in the halo

\[-\nabla \cdot [D(r, z, p)\nabla f - u(r, z)f] + \]
\[\frac{1}{p^2} \frac{\partial}{\partial p} \frac{p^2}{p^2} \left[ \left( \frac{dp}{dt} - \frac{\nabla \cdot u}{3}p \right)f - \kappa(r, z, p) \frac{\partial f}{\partial p} \right] = Q(p, r)\delta(z)\]
The Model of Electron Re-acceleration by Fermi II in the Galactic Halo (Cheng et al. 2014)

- Re-Acceleration of Relativistic Electrons emitted by SNRs

\[ -\nabla D(r, z, p) \nabla f + \frac{1}{p^2} \frac{\partial}{\partial p} p^2 \left[ \frac{dp}{dt} f - \kappa(r, z, p) \frac{\partial f}{\partial p} \right] = Q(p, r) \delta(z) \]

- Spectrum of CRs in the re-acceleration region
Spectra of re-accelerated CRs in the diffusion model
Wind structure in the Galactic central region

Mou, G., Yuan, F., Bu, D. et al. 2014
Adiabatic losses of CRs in the halo. Velocity of the shocks in the exponential atmosphere

Fig. 2.— Distribution of top shock velocity in the halo: $W = 3 \times 10^{55}$ erg (solid line) and $W = 10^{54}$ erg (dashed-dotted line)
\[-\nabla \cdot [D(r, z, p) \nabla f - u(r, z)f] + \\]
\[\frac{1}{p^2} \frac{\partial}{\partial p} p^2 \left[ \left( \frac{dp}{dt} - \frac{\nabla \cdot u}{3} p \right) f - \kappa(r, z, p) \frac{\partial f}{\partial p} \right] = Q(p, r) \delta(z)\]
• efficient adiabatic losses are necessary in the FBs (vertical galactic wind) in order to produce the needed microwave spectrum: \( u(z) = 3vz \)

• Three-dimensional hydrodynamical simulations of Mou et al. 2014 showed a strong winds in the FBs caused by accretion in Sgr A*, which is collimated by Central Molecular Zone towards the Galactic poles, i.e. perpendicular to the Galactic Plane.

• The wind velocity \( \sim 1100 \text{ km/s} \) (Carretti et al. 2013)

• Our analysis: in order to reproduce the FB gamma-ray and radio spectra:
  - the time of stochastic acceleration \( \sim 2 \cdot 10^6 \text{ yr} \)
  - the wind gradient \( \sim v \sim 10^{-15} \text{ s}^{-1} \)
Spectra of re-accelerated CRs without (left column) and with the Galactic wind (right column)
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Hadronic Model (Crocker & Aharonian, 2011)

• Lifetime of protons generating 100 GeV gamma-ray photons \( \sim 10^{10} \) yr, that of electrons \( \sim 10^{5} \) yr;

• Protons distribution in the bubbles is uniform. (However, the protonic scenario requires some sort of magnetic structure ("magnetic walls") able to confine the Bubbles’ protons for long times.);

• Flattening of the gamma-ray spectrum at \( E_\gamma < 1 \) GeV (the pp reaction threshold);

• Sources of CRs – star formation region in the inner \( 1^\circ \times 1^\circ \) CG region. Total power injected by SN there is estimated as \( \sim 10^{40} \) erg/s, that gives \( \sim 10^{39} \) in CRs and about \( 4 \times 10^{37} \) in 1 to 100 GeV gamma;

• Electrons are secondary which are transported to the halo form the disk. There synchrotron luminosity in the 20-60 GHz derived from gamma is \( 2 \times 10^{36} \) erg/s.

• If the characteristic time of transport by advection is \( z<3 \) kpc then \( \Phi_\nu \propto \nu^{-0.5} \), otherwise an additional electron component is necessary.
Spatial distribution of Bubble gamma-ray emission in the hadronic model

Excess of the gas density near the Bubble edges?
Problem of the hadronic model is a relatively hard microwave spectrum $\nu^{-0.5}$ spectrum of radiating electrons $E^{-2}$ spectrum of secondary electrons $E^{-3}$

$$\frac{1}{p^2} \frac{\partial}{\partial p} p^2 \left[ \left( \frac{dp}{dt_{\text{synch+IC}}} \right) f \right] = \int n_H \sigma_{pp} c N_p \, dp_p$$

$$N_{Se} \propto E^{-\gamma}$$

$$\Phi \propto \nu^{-\alpha}$$

$$\alpha = \frac{\gamma - 1}{2} = 1$$
Additional component of primary electrons is necessary

- The pure hadronic model is unable to reproduce the gamma-ray and radio fluxes from the FBs because the secondary electrons have too-soft spectrum $\propto E_e^{-3}$
- An additional component of primary electrons with a hard spectrum $\propto E_e^{-2}$ is necessary

The range magnetic field permitted for the hadronic model is within the 2–7 $\mu$G region.

- $pp$ collisions can only provide about 80% of the FB gamma-ray flux under the most favorable conditions when $H \sim 5$ $\mu$G which decreases for higher and lower values of $H$. The $pp$ mechanism is unable to generate the Bubble gamma ray flux if $H > 7$ $\mu$G or $H < 2$ $\mu$G.
Hadronic model with convection. Equation for secondary electrons.

\[-\nabla [D \nabla f - u(z)f] + \frac{1}{p^2} \frac{\partial}{\partial p} p^2 \left[ \left( \frac{dp}{dt_{sync}+IC} - \frac{\nabla u}{3} p \right) f \right] \]

\[= \int n_H \sigma_{pp} c N_p \, dp_p\]
Hadronic model with convection

• The model can provide 100% and 100% microwave emission if $\tau_{ad} < \tau_{IC+syn}$.
• The adiabatic losses are
  \[
  \frac{dE}{dt} = -E \frac{\nabla \cdot u}{3}
  \]
• This requires the wind gradient for $u = 3\lambda z$, the required gradient of the wind in the halo is $\lambda \sim 10^{-14} \text{s}^{-1}$
• However, the magnetic field higher than 20 $\mu$G, and power of CR sources larger than $10^{41}$ erg/s are required.
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• Fermi Bubbles are giant structures seen in the GC in gamma ray and microwave energy ranges. They are elongated in the direction perpendicular to the Galactic plane, size~ 5-8 kpc.
• Their spectrum both energy ranges is harder than the diffuse Galactic emission. The fluxes are $F_\gamma \sim 4 \times 10^{37}$ erg/s in gamma-rays and $\Phi_r \sim (1 - 5) \times 10^{36}$ erg/s in microwave ranges.
• The morphology similarity and correlation between GHz and gamma-ray GeV luminosities implies that the bubbles are real and their multi-wavelength emissions have common origin.
• It is assumed that the bubbles are generated due to processes of giant energy release in the vicinity of the central supermassive black hole: either a hypothetical single capture one million years ago of a very massive object (molecular cloud?) - $M \sim 10^5 M_\odot$, energy release $W \sim 10^{56}$ erg or due to routine star captures with the period 10-100 thousand years. Alternatively, star formation regions in the GC.
• Gamma-rays can be generated either due to the Compton scattering of relativistic electrons on background photons or due to collisions of relativistic protons with background gas (pp collisions).
Conclusion II (models)

• In the case of leptonic origin electrons should be produced in-situ i.e. high above the Galactic plane.
• For the case of hypothetical stochastic acceleration of electrons from background plasma a shortage of the model is that parameters of acceleration is strongly restricted. Either acceleration does not produce enough electrons or instead of the acceleration overheats the background plasma (no nonthermal tails).
• A advantage of stochastic re-acceleration of electrons emitted by SNRs in the Disk is that the injection energy of electrons is about 1 GeV (cf with the case of acceleration from background plasma where the injection energy is about hundred eV). However in this case effective adiabatic losses are required in order to get necessary spectral characteristic of the emission.
• The problem of hardonic model is a very steep spectrum of secondary electrons. Therefore an additional component of primary electrons with a hard spectrum is needed. In this case the protons produce no more than 70% of the total gamma-ray flux, the rest is produced by hypothetical component of primary electrons. The contribution of protons into the gamma-ray flux depends strongly on the magnetic field strength which should be in the limits 2–7 μG.
• The pure hadronic origin of gamma rays from the Bubbles is possible for a very strong galactic wind. But in this case the model require a very high power of the acceleration mechanism, \( \times 10^{41} \text{erg/s} \).
Thank you very much!!

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