Fermi bubbles

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RICAP, Rome
June 22, 2016
Su, Slatyer, Finkbeiner, May 2010

- $E^{-2}$ spectrum up to 100 GeV
- have narrow edges
- stretch up to $55^\circ$ above and below the Galactic center
Fermi bubbles – an elephant in gamma-ray sky

• Fermi bubbles’ solid angle is about 1 sr
  – This is comparable to an elephant at 3 m
Fermi-LAT

- Fermi Large Area Telescope – gamma ray space telescope
- Launched on June 11, 2008
  - 20 MeV to more than 1 TeV
  - 2.4 sr field of view
  - Better than 1° resolution above 1 GeV
  - Covers the sky in two orbits (3 hours)
Haze

- Microwave haze


- Gamma-ray haze


Fermi bubbles origin

- Emission mechanisms
  - Leptonic (inverse Compton)
  - Hadronic

- Origin
  - AGN-like activity (~ leptonic)
  - Star formation or star-burst (~ hadronic)
Leptonic Model

- Electrons accelerated in the jet
- Gamma rays by inverse Compton scattering on radiation fields
- Microwave haze by synchrotron of same population of electrons

- Illustrations by P. Mertsch

- Disruption of stars or molecular clouds by central black hole
- AGN-like jet transports particles to high latitudes
- Jets interact with interstellar medium to form bubbles

Hadronic Model

- Cosmic rays accelerated by Supernovae shells
- Gamma rays by $\pi^0$ on thermal gas (density $\sim 0.01$ cm$^{-3}$)
- Secondary $e^+e^-$ produce synchrotron radiation

Aharonian & Crocker, PRL, 106 (2011)

Illustrations by P. Mertsch
Gamma-ray spectrum

**Leptonic model**

- ICS, $b = 30.5$ deg ($z = 5$ kpc)
- ICS on CMB
- Fermi bubbles

**Hadronic model + secondary IC**

- $N_p \propto p^{-2.0} e^{-p/4.2 \text{TeV}}$
- $N_p \propto p^{-2.1}$
- Fermi bubbles


- Both leptonic and hadronic models fit the spectrum

Dmitry Malyshev, Fermi bubbles
Microwave haze

Leptonic

Hadronic (secondary leptons)

|l| < 25° and -35° < b < -10°

Planck Collaboration
A&A 554 (2013)


- Synchrotron emission from secondary leptons in hadronic models cannot explain the microwave haze
• At latitudes $|b| > 10^\circ$, the spectrum is uniform

\[ E^2 \frac{dN}{dE} \text{ (GeV)} \]

\[ 10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 10^0 \quad 10^1 \quad 10^2 \quad 10^3 \]

\[ 10^{-7} \quad 10^{-6} \quad 10^{-5} \quad 10^{-4} \quad 10^{-3} \]


• Natural in hadronic models
• In leptonic models the velocity should be $> 10000 \text{ km/s}$ to avoid $e^+e^-$ cooling before they reach $z \sim 10 \text{ kpc}$ distance
  – stochastic reacceleration: Mertsch & Sarkar PRL 107 (2011)
• Narrow boundary
  – Natural in AGN models – result of expansion
  – In star-formation models, one needs a mechanism that keeps CR from escaping, e.g., magnetic draping

• Absence of a shock
  – Natural in star-formation / hadronic models
  – In leptonic models one needs to (re)accelerate electrons
More puzzles

- **X-rays**
  - **ROSAT**
    - Su, Slatyer, Finkbeiner

- **Suzaku**
  - **Pointings**
  - **Emission measure**

- **Polarization**
  - **S-PASS, 2.3 GHz**
  - **WMAP, 23 GHz** polarization
  - **Planck, 30 GHz** polarization
    - Adam et al (Planck), arXiv:1502.01582

<table>
<thead>
<tr>
<th>Feature</th>
<th>Leptonic</th>
<th>Hadronic</th>
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<tbody>
<tr>
<td>Energy spectrum</td>
<td>✔</td>
<td>with secondary IC</td>
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<tr>
<td>WMAP / Planck haze</td>
<td>✔</td>
<td>extra component</td>
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<td>Isotropic emission</td>
<td>reacceleration</td>
<td>✔</td>
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<tr>
<td>Narrow boundary</td>
<td>✔</td>
<td>magnetic draping</td>
</tr>
<tr>
<td>No visible shock</td>
<td>?</td>
<td></td>
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</tbody>
</table>
AGN or starburst

- Often happen together
- Evidence for an AGN-like activity 0.5 – 5 Myr ago
  - Magellanic stream ionization
  - Young (~ 6 Myr) stellar population near the GC (~ $10^4 \, M_{\odot}$)


OB supergiants
  (~ few Myr lifetime)

Galactic center and the Fermi bubbles

- Fermi bubbles spectrum for $|b| < 10^\circ$

- Is it a part of the Fermi bubbles or a separate component?
- Options
  - Only bubbles
  - No bubbles
  - Both the bubbles and a new component

Dmitry Malyshev, Fermi bubbles
Fermi bubbles at low latitudes

• Assume that the bubbles have the same spectrum near the GC as at high latitudes $\sim E^{-2}$ between 1 and 10 GeV

• Subtract $\pi^0$ component and PS from data and represent the residual using two components:
  – Bubble-like $\sim E^{-2}$
  – Other components (IC, ISO, Loop I etc.) $\sim E^{-2.4}$

Data – gas – PS  $\sim E^{-2}$ component  Bubbles template

• Fermi bubbles template near the GC:
  – Larger intensity
  – Displaced to the right from the GC
Fermi bubbles near the GC

- Center of the Fermi bubbles intersection with the Galactic plane:
  \[ \sim 1^\circ - 2^\circ \text{ or about } 100 - 300 \text{ pc to the right of the GC?} \]

Fermi LAT Pass 7 diffuse model

Fermi LAT analysis of the GC excess?

Calore et al GC excess analysis?

Displacement of the GC excess:

Fermi bubbles

Galactic longitude (deg)

Galactic latitude (deg)

Residual 1.6 – 10 GeV

Acero et al (Fermi LAT)
ApJS 223 (2016)

Ajello et al (Fermi LAT)

Calore et al,
JCAP 1503 (2015)
Future

- **eROSITA**
  - Search for cavity in hot gas plasma due to CR pressure inside the Fermi bubbles

- **HESS, MAGIC, VERITAS, CTA, HAWC**
  - Fermi bubbles near the GC seem to be brighter
  - Possible to see with Cherenkov telescopes?

- **IceCube, KM3net**
  - Search for neutrinos from the Fermi bubbles

- **More analysis of existing data**
  - Fermi LAT (Pass 8 data)
  - Planck polarization
Conclusions

• Fermi bubbles are a unique feature on gamma-ray sky
  – Relatively bright in gamma rays
  – No clear counterpart at high latitudes in X-rays or radio
• Possible origin and emission mechanisms
  – AGN-like activity of Sgr A* (IC gamma rays)
  – Enhanced star formation near the GC (π⁰ gamma rays)
    • Both scenarios have advantages and disadvantages
• Tentative characterization at low latitudes:
  – Enhanced intensity near the Galactic plane
  – Displaced to the right (negative longitudes) from the GC
• Origin of the Fermi bubbles is an exciting question
  – Should learn more soon using new data from
    • eROSITA, CTA, IceCube and KM3net