Credits: Ettore Carretti, CSIRO (radio image); S-PASS survey team (radio data); Axel Mellinger, Central Michigan University (optical image); Eli Bressert, CSIRO (composition).
The Giant Magnetized Outflow from the Galactic Centre

Roland Crocker
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Gamma Ray Sky Minneapolis 2013
Fermi Bubbles

Fermi data reveal giant gamma-ray bubbles

Planck images a giant eruption from the heart of the Milky Way

The Galactic haze/bubbles is shown here in Planck data from 30-44 GHz

The same structure at 2-5 GeV as seen by the Fermi Gamma-Ray Space Telescope

A multi-wavelength composite image showing both microwaves and gamma-rays: Planck 30 GHz (red), 44 GHz (green), and Fermi 2-5 GeV (blue).

Slide credit: D. Pietrobon & K.M. Gorski
Planck Collab.
Fermi Bubbles

• $2 \times 10^{37}$ erg/s [1-100 GeV]

• hard spectrum, but spectral down-break below $\sim$ GeV in SED

• uniform intensity

• sharp edges

• vast extension: $\sim 7$ kpc from plane

• coincident emission at other wavelengths
Fermi Bubbles: Two Interlocking Questions

1. What is the radiation mechanism?

Cosmic ray electrons/Inverse Compton emission

OR Cosmic ray protons/gas collisions

2. What energizes the outflow?

Recent Seyfert-like activity of Sgr A*

OR Nuclear star formation ...OR [...]

Leptonic Scenarios

• $\sim$GeV $\gamma$-ray emission from IC by hypothesised population of hard-spectrum $\sim$TeV electrons

• same population synchrotron-radiates into microwave frequencies

• BUT short cooling time (Myr) $\Rightarrow$ relativistic transport OR in situ acceleration

• related to AGN-type activity
Hadronic Scenario
Crocker & Aharonian PRL 2011

• Bubbles’ gamma-ray luminosity requires a source of protons of power $\sim 10^{39}$ erg/s in saturation

• hard spectrum explained if protons confined in bubbles $\rightarrow$ the in situ spectrum shape = injection spectrum shape

• spectral down-turn below GeV explained by $\pi^0$ decay kinematics
• uniform intensity $\Rightarrow$ saturation scenario

• secondary electrons generate microwave emission of correct luminosity to reproduce WMAP Haze

• BUT low $n_H \Rightarrow$ long pp cooling time ($\sim$few Gyr)
Proton saturation scenario

- But shouldn’t the $\pi^0$ decay $\gamma$-rays trace the matter column density?
- Not in saturation (= thick target + steady state)

\[ L_\gamma \approx N_p / t[pp \rightarrow \pi^0] \]
\[ N_p \approx \partial_t Q_p \ t[pp] \]
\[ t[pp] \approx 3 t[pp \rightarrow \pi^0] \]
\[ \Rightarrow L_\gamma \approx \partial_t Q_p / 3 \]

\[ t[pp \rightarrow \pi^0] \propto 1 / n_H \] (in saturation)
Proton saturation scenario

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\[
L_\gamma \approx \frac{N_p}{t[pp \mapsto \pi^0]} \\
N_p \approx \partial_t Q_p \ t[pp] \\
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\Rightarrow L_\gamma \approx \frac{\partial_t Q_p}{3}
\]

\[
t[pp \mapsto \pi^0] \propto \frac{1}{n_H}
\]

...around 1/3 proton power emerges in $\gamma$-rays over all energies independent of $n_H$
A New Twist on the Fermi Bubbles

PI: Ettore Carretti, Roland M. Crocker, Lister Staveley-Smith, Marijke Haverkorn, Cormac Purcell, B. M. Gaensler, Gianni Bernardi, Michael J. Kesteven, Sergio Poppi

Nature 2013, 493, 66
S-PASS Survey

2.3 GHz RC polarization survey of southern sky with Parkes 64-m single disk, 184 MHz BW
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‘The Dish’, 51 years old
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‘The Dish’, 51 years old
The ‘S-PASS Lobes’

Northern Ridge

Galactic Centre Spur

Southern Ridge

limb brightening spurs

Jy/beam, beam size of 10.75’
The ‘S-PASS Lobes’

- Northern Ridge
- Galactic Centre Spur
- Southern Ridge
- Limb brightening spurs

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The ‘S-PASS Lobes’

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The ‘S-PASS Lobes’

- Northern Ridge
- Galactic Centre Spur
- Southern Ridge
- Fermi Bubble edge
- 60° ⇒ 8 kpc
- limb brightening spurs

Jy/beam, beam size of 10.75'
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The ‘S-PASS Lobes’

- Northern Ridge
- Galactic Centre Spur
- Southern Ridge
- Fermi Bubble edge

Polarization fraction: 25-30%

$60^\circ \Rightarrow 8 \text{kpc}$

Jy/beam, beam size of 10.75'
depolarization phenomenon implies in Bulge
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23 GHz Polarized Intensity from WMAP

WMAP PI + magnetic angle

Galactic Centre Spur
Northern Ridge
NW limb brightening
SW limb brightening
NE limb brightening
Southern Ridge
**Significant points**

Polarized, non-thermal emission
Spectral steepens with distance from plane

- detecting synchrotron emission from electron population advected from plane
Spectral index between polarized 2.3 and 23 GHz emission

Linearly-polarized emission interior to the Lobes spans the range

\[ \alpha = [-1.0, -1.2] \quad (S_\nu \propto \nu^{\alpha}) \]
**Significant points**

High polarization fraction, 25-30%  
⇒ rather regular magnetic field structure

Equipartition argument points to magnetic fields 6-12 μG for Lobes, ~15 μG for Ridges  
⇒ $U_B[\text{Lobes}] \sim (1 - 3) \times 10^{55}$ erg  
⇒ $U_B[\text{Ridges}] \sim 10^{53}$ erg

Broadband data imply magnetic field lower limits close to equipartition field amplitudes
What are the Ridges?

Geometrical interpretation: windings around the front surface of a biconical outflow

Sense of Galactic rotation + angular momentum conservation explain geometry

This explanation requires that we cannot see (putative) Ridges on rear side

If footpoints of the Ridges rotate with gas/stars around the GC at $v_{\text{rot}} \sim 80$ km/s, $r \sim 100$ pc, then geometry implies that they are expanding at $v_{\text{vert}} \sim 1100$ kms ($> v_{\text{esc}} \sim 900$ kms)
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Significant points

Plumes illuminated by electrons advected from plane

Outflow gathers to tight waist in Galactic plane, only 100-200 pc across

This encompasses the ‘Central Molecular Zone’
Figure S3: Linear polarization emission component Stokes U at 23 GHz from WMAP. An
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Figure S3: Linear polarization emission component Stokes U at 23 GHz from WMAP$^8$. An
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Herschel SPIRE 250 $\mu$m
(Molinari et al. 2011)
Herschel SPIRE 250 μm
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Herschel SPIRE 250 µm (Molinari et al. 2011)
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HESS TeV (Aharonian et al 2006)
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Ring collimates outflow -
outflow ablates cold gas

HESS TeV (Aharonian et al 2006)
Herschel SPIRE 250 μm (Molinari et al. 2011)

‘CMZ’ : ~5% Galaxy’s (massive) star formation

Ring collimates outflow - outflow ablates cold gas

HESS TeV (Aharonian et al. 2006)
Significant points

The radio continuum emission from the Central Molecular Zone is in significant deficit with respect to the expectation afforded by the Far-infrared-Radio Continuum Correlation.

BUT the Lobes’ radio continuum emission saturates the FRC-derived expectation applied to the CMZ.

Good evidence that we are seeing a star-formation-driven phenomenon.
FIR-RC

Yun et al. 2001 ApJ 554, 803 fig 5

\[ L_{\text{1.4 GHz}} = 1.5 \times 10^{20} \text{ Watt/Hz} \]

\[ L_{60\mu m} = 1.3 \times 10^8 L_\odot \]
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Fig. 1. Gamma-ray luminosity (0.1-100 GeV) versus total IR luminosity (8-1000μm).
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What are the Ridges?

\[ U_B \sim 10^{53} \text{ erg} \]

\[ \implies \sim 10^3 \text{ SN} \]

\[ \implies \text{formation} \sim 10^5 M_\odot \text{ of stars} \]

\[ \implies \text{mass of a super-stellar cluster} \]

Idea: the Ridges are energised by - and have footpoints associated with - the super-stellar clusters orbiting the GC

In this interpretation the Lobes/Ridges are a phonographic record of the last few Myr of star formation in the GC
Work in progress: $10^8$ year hadronic model

H$\alpha$ filaments NGC 1275 (Perseus Cluster)

Fabian et al. 2008
Work in progress: $10^8$ year hadronic model
Extra Slides
Problem for electrons

The graph shows the relationship between time ($t$) in years and energy ($E$) in electron volts ($eV$). The curves represent different time scales ($t_{\min}$, $t_{\max}$) and energy scales ($1$ GeV, $100$ GeV). The graph includes annotations for $10$ kpc, $1000$ km/s.
Problem for electrons
Problem for electrons

- $t_{p,\text{max}}$
- $t_{e,\text{max}}$
- $t_{\text{inj}}^{\min}$

- 10 kpc, 1000 km/s
- 1 GeV ($\pi^0$)
- 100 GeV ($\pi^0$)
- 1 GeV (IC)
- 100 GeV (IC)

$E/\text{eV}$ vs. $t/\text{year}$
Gas/Wind/Mag. Field

![Diagram showing the relationship between wind speed, magnetic field strength, and hydrogen densities.](image)

- The x-axis represents $n_H^{\text{HESS}}$ (hydrogen density) in $\text{cm}^{-3}$.
- The y-axis represents $V_{\text{wind}}$ (wind speed) in $100\text{km/s}$.
- Horizontal bands indicate different magnetic field strengths: 1 mG, 300 $\mu$G, and 100 $\mu$G.

Legend:
- $e$ for electrons
- $p$ for protons
Gas/Wind/Mag. Field

The diagram shows the relationship between wind velocity ($V_{\text{wind}}$) and hydrogen density ($n_H$) in a graph. The $x$-axis represents $n_H$ in units of $\text{cm}^{-3}$, and the $y$-axis represents $V_{\text{wind}}$ in units of km/s. Key labels include $e$, $p$, $n_{H\text{H}^+}$, and $\langle n_H \rangle_{\text{vol}}$. The graph includes lines indicating different values of magnetic field, such as 1 mG and 300 $\mu$G, and highlights specific regions with different colors.
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