The elephant in the Galaxy: Giant magnetised outflows from the Centre of the Milky Way

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What are the Fermi “Bubbles”?

- They were recently discovered in the data of the Fermi gamma-ray telescope by Su, Finkbeiner & Slatyer (2010, ApJ, 724, 1044).

- They are enormous, bilateral “bubbles” of emission extending to 50 degrees from the Galactic plane.

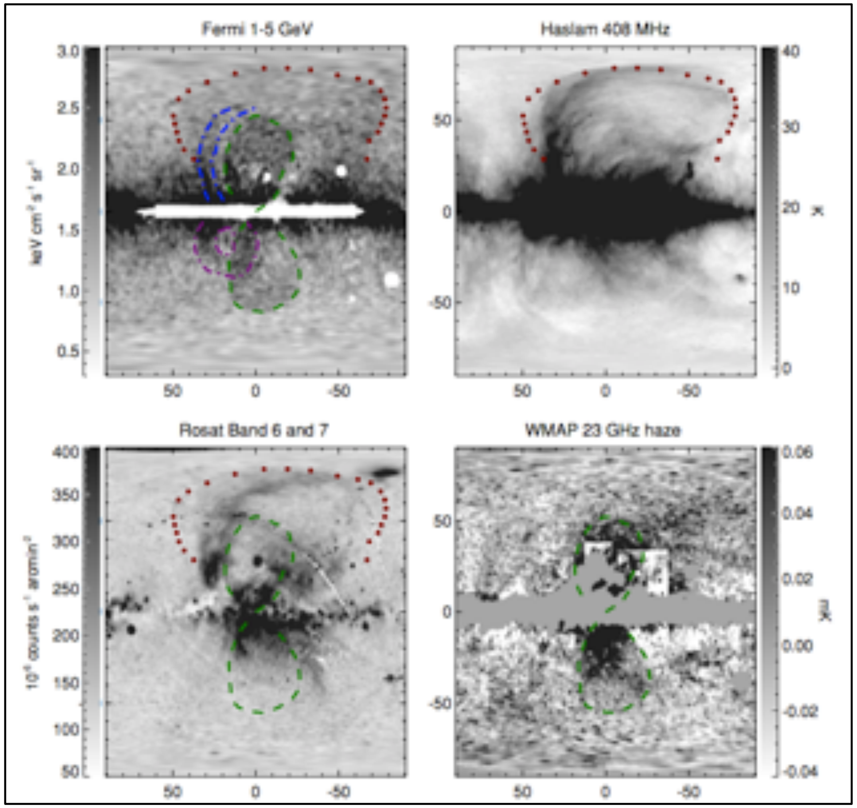
- Robustly detected in the residual images from the 1.6-year Fermi data between 1 and 100 GeV.

- No significant spatial variation in the spectrum, gamma-ray intensity within the bubbles, or between the north and south bubbles.

Source: http://article.wn.com/view/2012/02/20/Fermi_telescope_unveils_gammaray_bursts_highest_power_side/

A Panchromatic View of the Fermi Bubbles

- Evidence of similar, possibly related large-scale structures in our Galaxy can also be observed at other wavebands.
    - This suggests a population of non-thermal particles pervading a large fraction of our Galaxy that are distinct from background cosmic-rays.



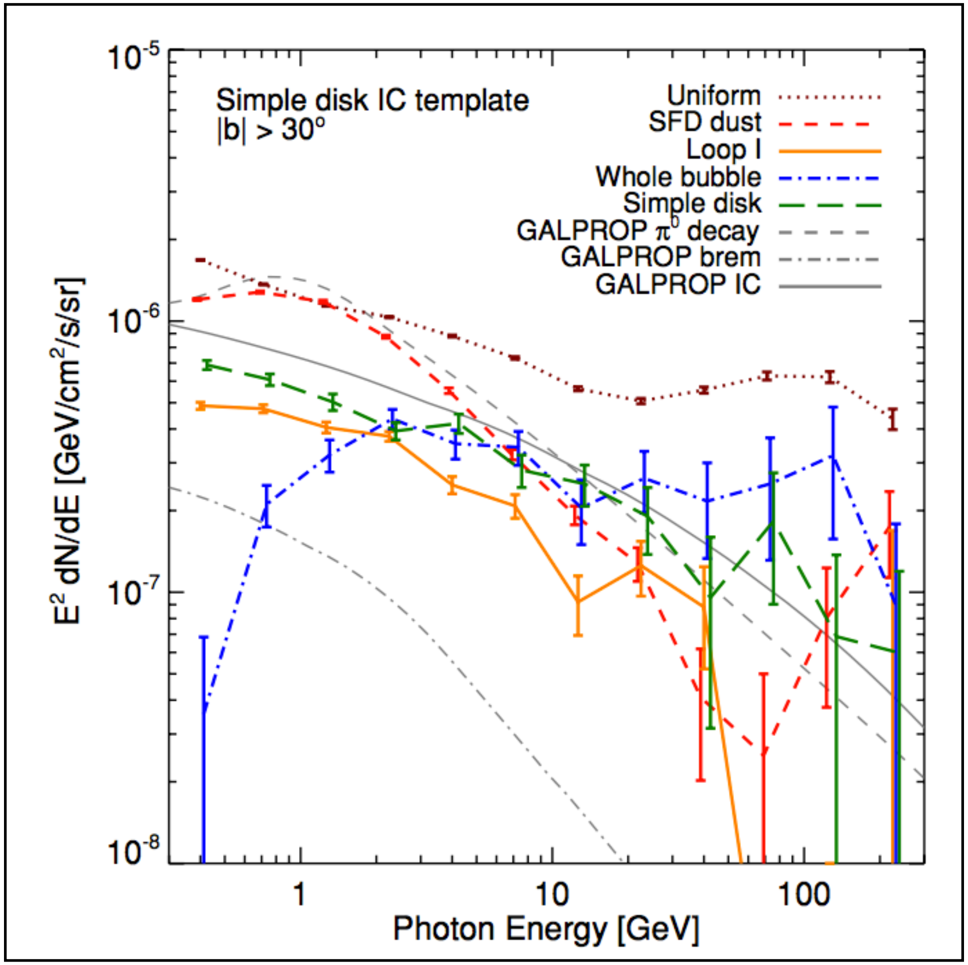
How were/are the Bubble Formed?

- The Bubbles are difficult to explain in a consistent manner due to:

  1. The **large luminosity** of ~4 × 10^{37} erg s^{-1} in the gamma-ray domain (an order of magnitude larger than the Bubbles' microwave luminosity but more than order of magnitude less than their X-ray luminosity; Su et al. 2010)

  2. A **hard spectrum** of dN/dE~E^{-2} from 1 to 100 GeV

  3. Their **vast extent** and relatively **uniform gamma-ray intensity**.



Su, Finkbeiner & Slatyer 2010, ApJ, 724, 1044

The trouble with electrons...

- The Bubbles could be revealed via inverse Compton (IC) losses of a population of electrons simultaneously producing the GeV and multi-GHz photons.

- Hypotheses for the acceleration of these electrons have included:
    - Bubble-pervading shocks (Cheng, K. S., et al., 2011, ApJL, 731, L17.), or distributed, stochastic, acceleration on plasma wave turbulence (Mertsch, P., & Sarkar, S., 2011, PhRvL., 107, 1101).
    - A prior outburst by an AGN-like outburst from the central black hole, Sgr A*, in the past few million years (Su, et al, 2010).

- However, electrons have trouble either producing the hard spectrum and/or filling the enormous volume of the Bubbles (Crocker & Aharonian, 2010) and the spectral downturn below ~1 GeV.

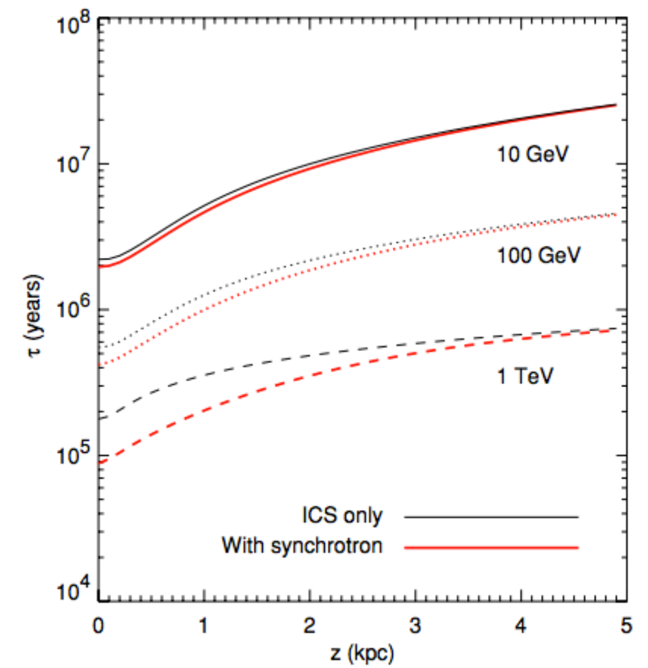


Figure 28. Cooling time for electron CRs as a function of energy and height above the Galactic plane, for $r = 0$. Thin black lines: synchrotron losses are neglected; equivalently, the B-field is assumed to be negligible everywhere. Thick red lines: The cooling time calculation includes synchrotron losses in a magnetic field given by $|B| = 30e^{-z/2\,\mathrm{kpc}}$ μG. We use the standard radiation field model from GALPROP version 50p, and define the cooling time $\tau = 1/(d \ln E/dt)$.

Su, Finkbeiner & Slatyer 2010, ApJ, 724, 1044

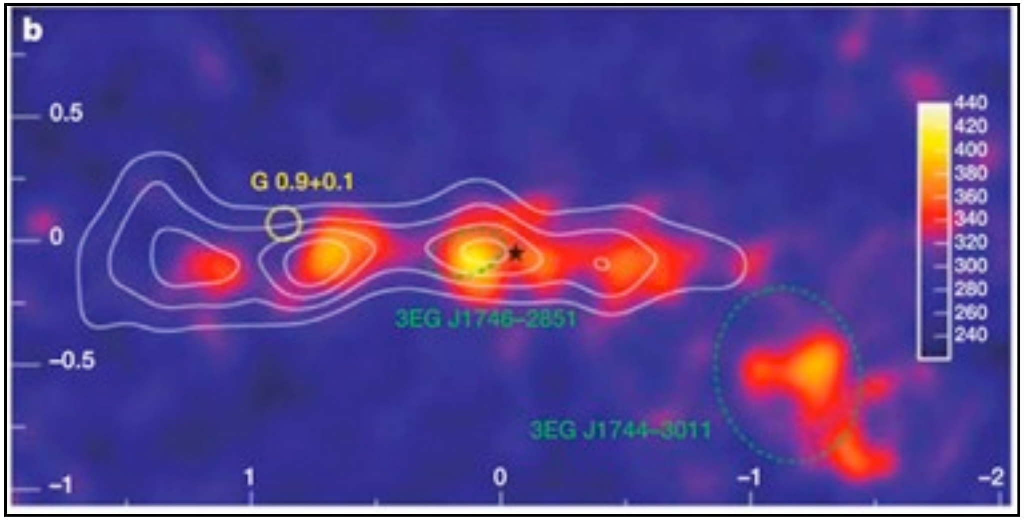
Protons to the rescue?

- An explanation that *can* reconcile the seemingly difficult parts of the Bubbles' nature are cosmic-ray protons (strictly CR protons + heavier ions).

- Here, CR protons, accelerated by supernovae in the Galactic centre region and advected into the Bubbles on a wind (Crocker & Aharonian, 2011, Crocker, Jones+, 2011, MNRAS, 411, 11 and Crocker, Jones+, 2011, MNRAS, 413, 763).

- The protons (that aren't advected) are also observed as the diffuse TeV gamma-ray glow in the Galactic centre (Crocker, Jones+ 2011, MNRAS, 411, 11).

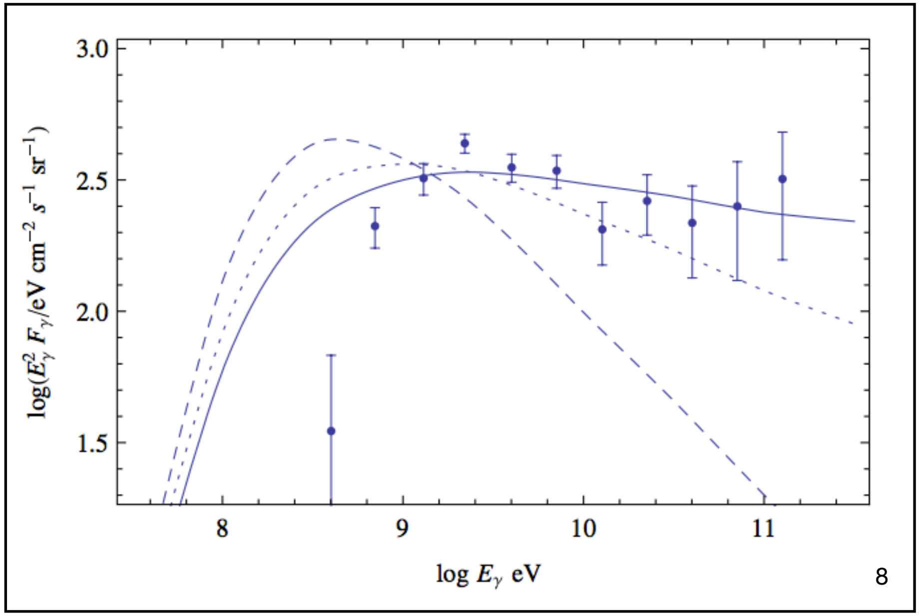
- This gives a prediction for the connection of the Bubbles: they should connect to the TeV gamma-ray "glow-points".



Aharonian, et al., 2006

Protons to the rescue?

- The advantages of the proton model is that it naturally explains:
  - The hard spectrum: there is no energy-dependent mechanisms steepening because of the advection of the protons on the wind.
  - The low-energy ‘bump’ seen in the Bubbles’ spectrum due to the kinematics of the *pp*-interactions.
  - Saturation (thick-target + steady-state) conspires to give the Bubbles a uniform intensity.
  - Saturation also implies a minimum formation timescale of ~10^{10} years.



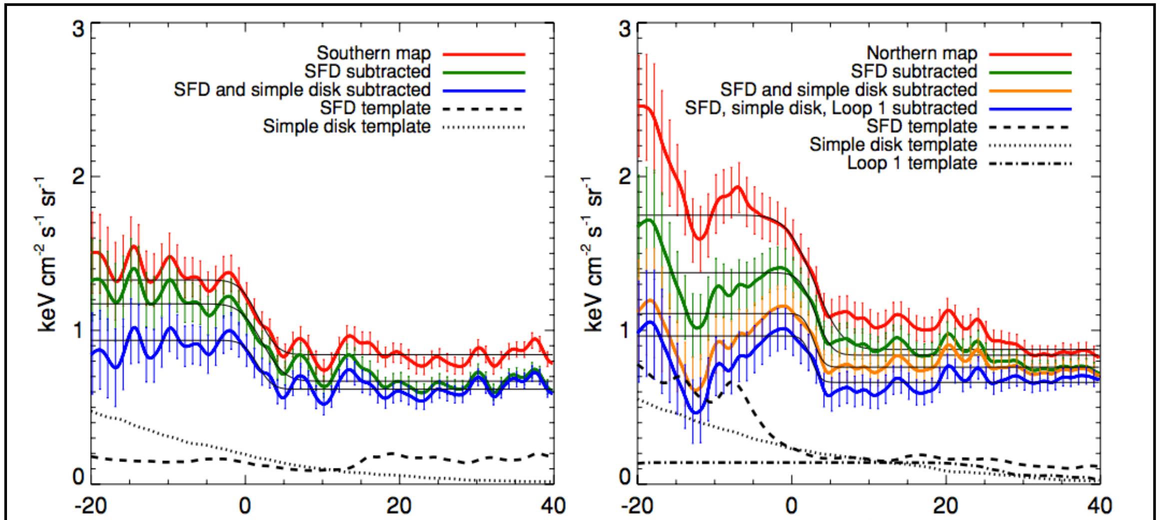
CR proton confinement in the Bubbles

- The confinement of the Bubbles does pose a problem for the proton scenario.

- However, “Diffusive confinement could achieve this alone for a diffusion coefficient 1–2 orders of magnitude smaller than the Galactic plane value...” (Crocker & Aharonian, 2011).

- Additionally, the edges of the Bubbles are rather “sharp”, and show evidence of high energy emission from the ROSAT “bi-conical” structures.

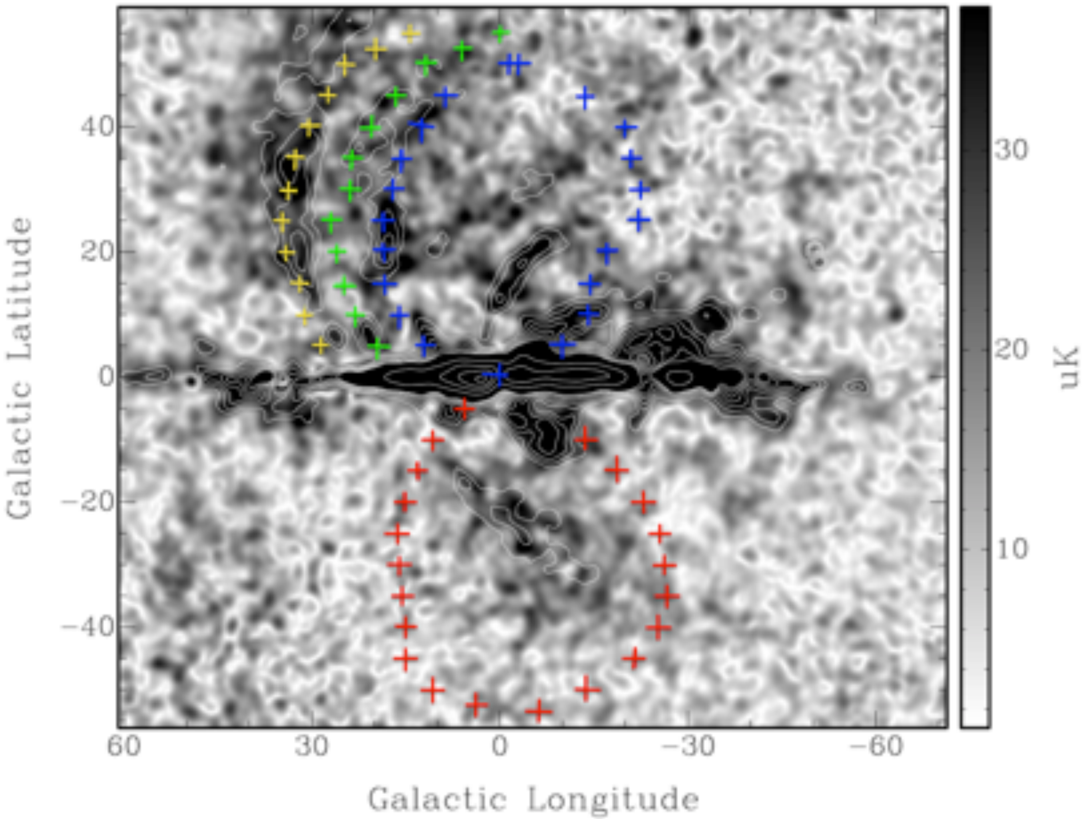
- Thus, there may be magnetic structures which evidence the confinement of the CR protons within the Bubbles...



Su, Finkbeiner & Slatyer 2010, ApJ, 724, 1044

Magnetic confinement in the Bubbles

- The 5-year WMAP polarisation emission data (especially at 23 GHz) *does* show evidence of magnetic structures that could be evidence of CR proton confinement.
- These polarised structures correspond to the Bubble structures seen at GeV energies.



Still missing is:

- A good model for the formation of the Bubbles:
  - Are they due to long-timescale star-formation in the Galactic centre accelerating *protons*?
  - Or are they due to *electrons* coming from a previous outburst of nuclear activity, or some in-situ re-acceleration of ambient cosmic ray electrons?
- Establishment of exactly where the Bubbles are:
  - Are they a Galactic centre phenomenon?
  - Or are they a local structure, like the North Polar Spur is?

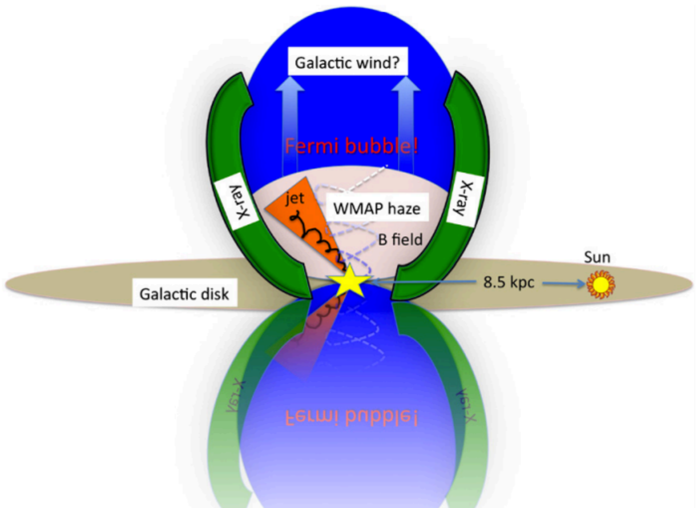
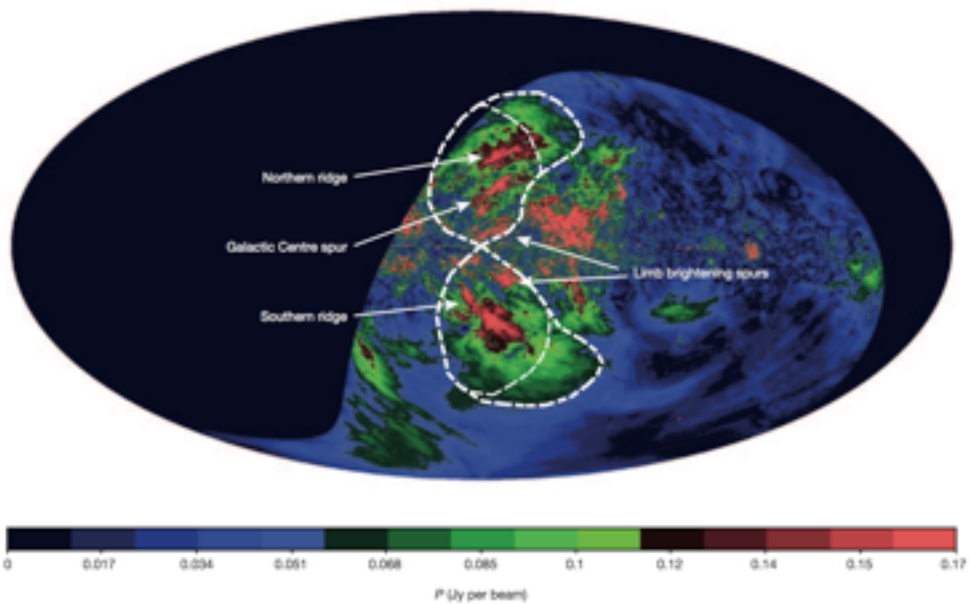


Figure 27. Schematic illustration to summarize the observations of the *Fermi* bubble structures. Two blue bubbles symmetric to the Galactic disk indicate the geometry of the gamma-ray bubbles observed by the *Fermi*-LAT. Morphologically, we see corresponding features in *ROSAT* soft X-ray maps, shown as green arcs embracing the bubbles. The *WMAP* haze shares the same edges as the *Fermi* bubbles (the pink egg inside the blue bubbles) with smaller extension in latitude. These related structures may have the same physical origin: past AGN activities or a nuclear starburst in the GC (the yellow star).

Su, Finkbeiner & Slatyer 2010, ApJ, 724, 1044

The S-PASS Lobes

- May answer the above questions…
- Discovered by the S-band Polarised All Sky Survey (done with Parkes; Caretti, et al., Nature, 2013, 493, 66), they are two giant, linearly polarised radio lobes, containing three ridge-like substructures, emanating from the Galactic Centre.
- The lobes each extend about 60 degrees in the Galactic bulge, closely corresponding to the Fermi bubbles, and are permeated by strong magnetic fields of up to 15 μG.



Why are they important?

- They **trace the Fermi bubbles** excepting the top western corners where they extend beyond the region covered by the gamma-ray emission structure.
- Depolarisation by HII regions establishes that the lobes are **almost certainly associated with the Galactic Centre**, implying that their height is ~8 kpc (Below, right).
- Along with a high polarisation fraction of 25%, the phenomenology and a (2.3 to 23 GHz) spectral index of ~-1, steepening to ~-1.2 with increasing height, indicates that the lobes **are due to CR electrons**, transported from the plane, synchrotron-radiating in a partly ordered magnetic field (Below, left).

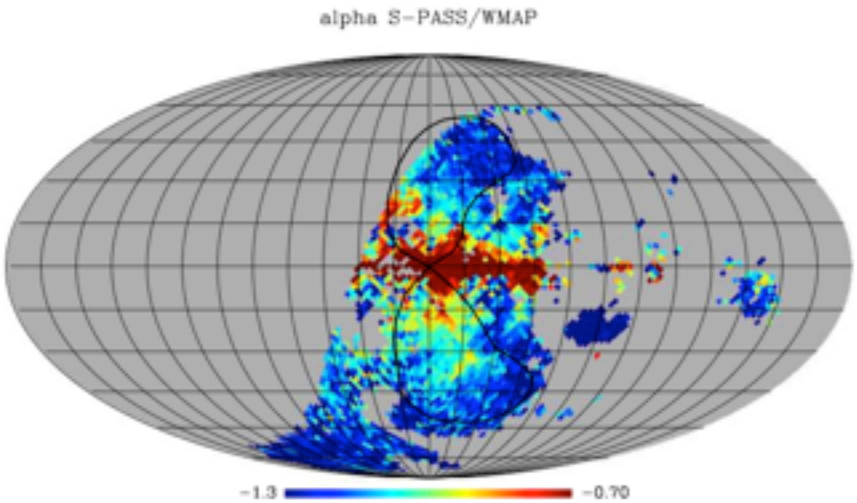


Figure S4: **Spectral index α between the 2.3 and 23 GHz polarized emission.** The flux density S is modelled as a power law of the frequency $S \propto \nu^{\alpha}$. The map is in Galactic coordinates, centred at the Galactic Centre. Grid lines are spaced by 15°. S-PASS and WMAP linear polarized emission maps have been binned in 2° × 2° pixels to improve the Signal-to-Noise ratio of the latter.

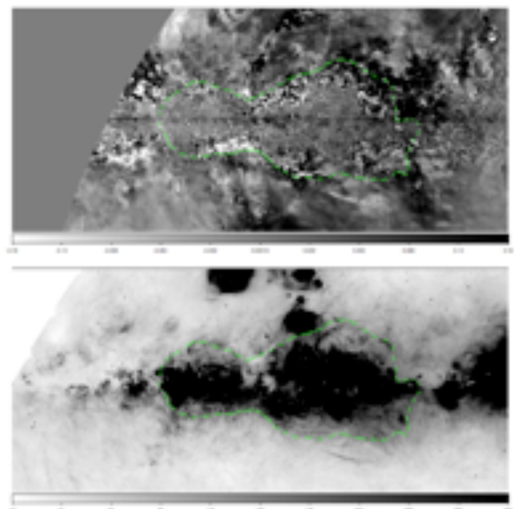


Figure S1: Top: **Stokes Q image of the area around the Galactic Centre.** The Galactic plane is horizontal across the picture and the emission unit is Jy/beam with a beam of FWHM=10.75'. The green dashed line indicates the two areas of depolarization on either side of the Galactic Centre and the belt encompassing them of emission modulated to small angular scales by Faraday Rotation effects. Bottom: **H-α emission image of the same area from the SHASSA survey**. The emission unit is decirayleighs (dR); The resolution is FWHM=6'. The area affected by Faraday Rotation effects is reported as well and corresponds to H-α emission regions from the Sagittarius and Scutum-Centaurus arms – see text.

LOFAR Observations of the Bubbles

- Why observe the Bubbles/S-PASS lobes with LOFAR?

- The northeast (top left) of the Bubbles/Lobes, is the brightest part of the Bubbles/Lobes and is most easily observed with LOFAR, so that because:

  - S-PASS observations seem to show that it does not to suffer electron losses along its length - does this occur along its entire length? If so, why? And what are the differences between that at the North Polar Spur (NPS; i.e., a local source)?

  - How well does the radio continuum emission at the edge match the gamma-ray emission (which are at similar energies to LOFAR "energies")? 408 MHz and Fermi gamma-ray observations are not sensitive (in resolution and sensitivity) enough to answer this question

  - Does the polarised emission (still ~25% at 2.4 GHz) continue down to LOFAR frequencies? If so, what are the differences/similarities between the Bubbles/Lobes and the NPS? What about the Bubble/Lobe interior?

  - What are the differences/similarities in Faraday-Rotation space of the Bubbles/Lobes, polarised ridges and the NPS?

LOFAR Observations of the Bubbles

- We have 20 hours to observe small parts of the Bubbles with LOFAR HBA (#s (i) & (iv) below).

- Will observe total and (hopefully) polarised intensity.

- These observations, though only a pilot programme, will hopefully help is to answer these questions and provide answer to the above questions.

Position	GLAT & GLON (deg.)	R.A. & Dec. (h.m.s.) & (d.m.s.)	K-band pol. (μK)	408 MHz[a] (Jy/beam)	150 MHz[b] (Jy/beam)	150 MHz pol.[b] (Jy/beam)
(i)	9.5, 50.25	15 16 26, +7 8 20	70	28	3.25	0.07
(ii)	18.5, 51.5	15 24 4, +12 38 14	60	10	1.2	0.024
(iii)	24.0, 34.75	16 31 59, +8 25 1	74	18	2.125	0.04
(iv)	32.25, 35.0	16 42 49, +14 38 50	105	9	1.06	0.02
(v)	33.25, 47.75	15 54 04, +19 55 43.1	72	16	1.9	0.04

Table 1: Details of selected fields within the Fermi Bubbles. It is important to note that the flux estimates at 150 MHz assume a beam-size of $\sim 3'$, and have been scaled from the beam-size of the 408 MHz observations to reflect this. [a] Flux is given at native 408 MHz resolution (0.81°) and for images which have been filtered of emission above scales of 2°. [b] Scaled flux densities and polarised densities have been calculated using a spectral index of $\alpha = -0.63$ [12] and a polarised-to-total intensity ratio of 0.02, respectively.

Conclusions

- Hopefully next time I give a talk, I will:
- Be able to show some LOFAR total and polarised intensity images of the Fermi Bubbles/S-PASS lobes...
- Be able to talk about the spectral and magnetic field structure of the Bubble/ Lobe walls...
- Be able to tell you something more about the origins of the Bubbles/Lobes...