Fermi Bubbles as AGN Laboratories: Supersonic Jets with Anisotropic Cosmic Ray Diffusion (arxiv: 1207.4185)

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Nonthermal emission from AGN lobes/bubbles

Centaurus A

- $U_{\text{CMB}} \sim 10U_B$
- 0.1-1 TeV $e^-$

Hydra A

H.E.S.S. Collaboration
Fermi bubbles – possible evidence for past jet activity of Sgr A*

- Morphology
- Flat intensity
- Sharp edges
- Hard spectrum
- ROSAT X-ray features
- WMAP Haze

Su 2010
Forming Fermi bubbles by CR jets

- 2D, hydro simulations including CR pressure, advection and diffusion
- Plausible to form bubbles within 2-3 Myr
- Axial ratio reproduced

- Large-scale instabilities
- Edge-darkened surface brightness

=> Viscosity may be at work
Why are the bubble edges sharp?

- Sharp edges imply suppression of CR diffusion across bubble surface
- Due to magnetic draping + anisotropic CR diffusion?
3D MHD simulations of CR jets with anisotropic CR diffusion

- **FLASH**, unsplit staggered mesh MHD solver, *new* CR module

- **Included physics**
  - CR pressure and advection
  - Ambient tangled *(mean)* magnetic fields
  - Injected magnetic fields (*f_B* = 1e-3; Sutter 2012, Li 2006)
  - Anisotropic CR diffusion (*κ_∥* = 4e28 or 1.2e29 cm²/s)

- **Jet parameters:**
  \[ η_j = 0.05, \ P_{jth} = 1.06e-9, \ P_{jcr} = 8.3e-10, \]
  \[ R_j = 0.5kpc, \ ν_j = 0.025c, \ t_j = 0.3Myr \]

- **Observational constraints**
  - Initial gas density profile (Miller 2012)
  - Bubble temperature ~ a few \(10^7\) K (Miller 2012) \(\Rightarrow R_j, \ ν_j\)
  - Limb-brightened X-ray image \(\Rightarrow η_j, t_j\)
  - Bubble axial ratio \(\Rightarrow P_{jth} + P_{jcr}\)
Supersonic jet-inflated Fermi bubbles – the pure-hydro case

- Projection of 3D bubbles $\Rightarrow$ short bubble formation time $\sim 1.2$ Myr
- Naturally satisfy age constraint from IC cooling time of high-energy electrons
- No sufficient time for instabilities to develop

- Edge-brightened CR distribution $\Rightarrow$ nearly flat surface brightness (in longitude)
Magnetic draping due to supersonic bubble expansion

- B fields amplified and aligned with bubble surface
- Draping more effective for fields initially parallel to bubble surface
- Draping more effective when $l_B > R_{\text{bub}}$
Anisotropic CR diffusion + magnetic draping => sharp bubble edges

- Bubble shape traces underlying B field if CR diffusivity is large
Not: Ram pressure from IGM, jet precession, BH motion

Both jets tilted to the east by $10^\circ$ for $0 < t < 0.1 t_j$, possibly due to SN ram pressure.
Either $P_{\text{CRe}} \sim 5 \times 10^{-4} P_{\text{sim}}$ or $P_{\text{CRp}} \sim P_{\text{sim}}$ could produce the observed gamma-ray.

Since $P_{\text{2nde}} < 1 \times 10^{-6} P_{\text{sim}}$, synchrotron is dominated by primary CRe.

$\Rightarrow$ Gamma-ray is also dominated by CRe

$\Rightarrow P_{\text{CRp}} \ll P_{\text{sim}}$

$\Rightarrow P_{\text{sim}} = P_{\text{CRe}} + P_{\text{CRp}} + P_{\text{th}}$ (thermal pressure dominates inside the bubbles)

Uncertainties

- Spectrum of CRe
- B fields inside the bubbles

Spectra averaged over $|l|<10^\circ$, $20^\circ<b<30^\circ$
How to get large enough strength and gradient of B fields inside the bubbles?

\[ B(z) \sim 50 \mu G \times \exp(-z/2\text{kpc}) \]

Higher latitude, \( l_B > R_{\text{bub}} \), more draping, B field evacuated more

Lower latitude, \( l_B < R_{\text{bub}} \), less draping, B field penetrated in

\[ \frac{\partial}{\partial z} \left( \frac{\partial B}{\partial z} \right) = 0 \]
Primary features of the Fermi bubbles are reproduced by our 3D MHD simulations, providing evidence for past AGN jet activity at the GC. Fermi bubbles are invaluable laboratories to study physics of CRs and B fields, and the compositions of AGN bubbles.

- CRe cooling due to IC and synchrotron losses
- CR acceleration by shocks, MHD turbulence, or fast magnetic reconnection