Fermi Bubbles:
MHD simulations of leptonic AGN jets

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Bubbles show energetic spectrum and sharp edges.
Haze emission

Simulations:

- Gas dynamics
- Cosmic ray pressure
- B-field-aligned cosmic ray diffusion
- Magnetic field
- ISRF + CMB

edge-enhanced CR distribution

flat sky-projected gamma-ray distribution
Gamma-ray spectrum

E\text{dN/dE} [GeV cm^{-2} s^{-1} sr^{-1}]

0.1 \quad 1.0 \quad 10.0 \quad 100.0 \quad 1000.0

E [GeV]

|b| = 30–50 deg.

Su 2010
Hooper 2013
Run A

6 kpc

0 kpc
Gamma-ray spectrum

Haze normalization/slope

assuming GALPROP’s

\[ |B| = B_0 \exp(-z/z_0) \exp(-R/R_0) \]

Haze normalization/slope
Magnetic draping $\textbf{sharp}$ bubble edges in gammas

CRs in contact with $\textit{weak}$ B-field ($\textit{weak}$ synchrotron emission)
Partial magnetic draping:

- bubble edges *still* sharp
- seed fields enter the bubble
Coherence length > Coherence length > Coherence length
Vorticity magnitude

Larsson & Lele (2009)
\[ B_{bubb} \leq (\alpha r)^{1/2} B_{amb} \]
Gamma-ray spectrum

Haze normalization/slope

6 kpc

0 kpc
B-fields strong enough to explain synchrotron

BUT at low-z

\[ \beta \sim \frac{P_B + P_{th} + P_{cr}}{P_B} \sim 1 \]

CR & gas are displaced

need CR replenishment near the center
B-fields strong enough to explain synchrotron

BUT at low-z

\[ \beta \sim \frac{P_B + P_{th} + P_{cr}}{P_B} \sim 1 \]

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need CR replenishment near the center
Su & Finkbeiner (2012)

See also: Li, Morris, Baganoff (2013) astro-ph posting yesterday

Sub-parssec X-ray Jet
Su & Finkbeiner (2012)

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Sub-parsecc X-ray Jet
Centaurus A
Haze profile matches data
Haze profile matches data

Gamma-ray profile nearly flat as observed
S-PASS data: Carretti, Crocker et al. (2013)
Angle between vorticity and x-axis:

90 degrees → 0 degrees

Larsson & Lele (2009)
Polarization fraction and sky-projected B-field
Rotation measure map
Deficient Haze emission $< -35$ degrees

Planck collaboration (2012)

suppressed CR number density (would contradict gamma map)

OR

suppressed B-field
2.3 GHz S-PASS data:

\[ B_{\text{eq}} \sim 6 \mu G \]

Beck & Krause (2005)

\[ \frac{e_{\text{cr}}}{e_B} = \left( \frac{B_{\text{true}}}{B_{\text{eq}}} \right)^{-\frac{p+5}{2}} \]

\[ e_{\text{CR,Re}} \sim f_{e,\nu} e_{\text{cr, sim}} \]

\[ e_{\text{CRp}} / e_{\text{CR,Re}} = 100 \]

\[ B_{\text{true}} \sim 2 \mu G \]

If \( e_{\text{cr}} > e_{\text{CR, sim}} \) then \( B_{\text{true}} < 2 \mu G \)
Bubble Composition

in the leptonic model:

same population of e-
explains WMAP and gamma

\[ e_{\text{CRE}} \sim f_e e_{\text{CR, sim}} \sim 5 \times 10^{-4} e_{\text{CR, sim}} \]

\[ k \equiv \frac{e_{\text{CRp}}}{e_{\text{CRE}}} \leq 200 \]

\[ e_{\text{CRp}} \sim f_p e_{\text{CR, sim}} \leq 0.1 e_{\text{CR, sim}} \]

Yang, Ruszkowski, Zweibel 2013
Yang, Ruszkowski, Ricker, Zewibel, Lee 2012
Guo, Mathews 2012
Guo, Mathews, Dobler, Oh 2012

in the hadronic model
one would need

\[ e_{\text{CRp}} \sim f_p e_{\text{CR, sim}} \sim e_{\text{CR, sim}} \]

\[ e_{\text{2nd e-, cumul}} \sim 5 \times 10^{-4} e_{\text{CR, sim}} \]

Yang, Ruszkowski, Zweibel 2013
Crocker & Aharonian 2011
Guo, Mathews 2012
Guo, Mathews, Dobler, Oh 2012
Key Points

- Same population of CR e- simultaneously explains Fermi gamma and WMAP emission
- Our simulations require second jet (in agreement with Su & Finkbeiner 2012)
- B-field amplification inside Fermi bubbles can be efficient (consistent with WMAP emission & S-PASS polarization data)
- Multiwavelength data allow us to an look inside the bubbles (leptonic model suggests weak CR pressure support)
- A separate low-energy CR population required to explain S-PASS emission; in agreement with Carretti et al. 2013
Postdoctoral Position in Theoretical Astrophysics - JRID45794
Larger scale fields

Smaller scale fields
Vorticity magnitude

Larsson & Lele (2009)
Ambient ISM
\[ e_{B,am} \sim e_{turb,am} \]

Shocked shell
\[ e_{turb,sh} \]

Bubble
\[ e_{B,bub} \sim e_{turb,bub} \]

\[ e_{turb,bub} \lesssim e_{turb,sh} = 0.5 \rho_{sh} \sigma_{sh}^2 \]

\[ 0.5 (r \rho_{amb}) (\alpha \sigma_{amb}^2) = \alpha r e_{turb,amb} \]

\[ B_{bubb} \leq (\alpha r)^{1/2} B_{amb} \]
Owen (NRAO), Biretta (STScI)
very early in the bubble evolution
only for the most energetic particles in the CR energy spectrum

\[ \min(t_{IC}, t_{\text{synch}}) > t_{\text{dyn}} \quad \text{for} \quad t < 0.1 \text{Myr} << t_{\text{Fermi}} \]
Arc features correlated with bubble edges

X-ray cavities suggest underdense bubbles
Figure 6. Simulated X-ray map at 1.5 keV (see the text for definition) for the same run as Figure 5. The solid and dotted lines show the surfaces of the observed northern and southern Fermi bubbles, respectively. The dashed lines are the inner and outer northern arcs observed by the ROSAT X-ray satellite.