Constraining the energy budget of radio galaxies with LOFAR

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Why is it important to constrain radio-galaxy energetics?

- AGN feedback appears necessary for galaxy formation.
- Radio outbursts thought to balance cooling in cluster centres
- Radio-loud AGN may play a role in explaining entropy excess in groups & clusters.

Blanton et al. 2001
The low-energy electron population

- Most of the energy density in radio galaxies and quasars is at energies below currently observable radio region.
- Radio-source properties depend strongly on assumed spectrum below $\sim 300$ MHz: $\alpha_{\text{low}}$ and $\gamma_{\text{min}}$.
- See discussion in Harris (2004, astro-ph/0410485)

Figures from Harris (2004)
X-ray IC emission from radio lobes

Croston et al. 2005, Hardcastle & Croston 2005
• X-ray IC emission gives probe of low-energy electrons & direct measurement of electron density.
• Can then calculate $B$ using radio synchrotron emission.
• Incident photon populations are CMB ($\nu \sim 10^{11}$ Hz) and nuclear IR/optical ($\nu \sim 10^{14}$ Hz) emission (e.g. Brunetti 1997).
• $\nu_{\text{out}} \sim \gamma^2 \nu_{\text{in}} \Rightarrow$
  - To scatter CMB to X-ray, need $\gamma \sim 1000$
  - To scatter nuclear IR/optical to X-ray, need $\gamma \sim 30 - 100$
• With current instruments we have to extrapolate down to these energies from the observable radio region.
A Chandra/XMM survey of radio-source electron content

X-ray/radio analysis

- 33 sources, 11 new detections, X-ray detection in at least one lobe in 70% of sources.
- Electron population modelled using radio spectrum:
  - 1.4 GHz maps with regions matched to X-ray extraction regions
  - 3C flux densities at 178 MHz
- Low-energy assumptions:
  - $\delta = 2$ (prediction from shock acceleration)
  - $\gamma_{\text{min}} = 10$
- Determine predicted X-ray IC/CMB emission at 1 keV for $B = B_{\text{eq}}$ for comparison with $S_{\text{obs}}$. 
Results

• Consistent with IC/CMB with \( B = (0.3 - 1.3) \, B_{eq} \)

• For our assumptions about low-energy electrons, typically predicted \( S_{\text{nuclear}} \ll S_{\text{cmb}} \).

• Peak in \( B \) distribution at \( B \sim 0.7 \, B_{eq} \)

• > 75% of sources at equipartition or slightly electron dominated

• Magnetic domination must occur rarely, if at all.

• Good agreement with equipartition argues against energetically dominant relativistic electron population.

• Total internal energy in FRII radio sources is typically within a factor of 2 of minimum energy.
Assumptions about low-energy electrons

- Cut-off frequency, $\gamma_{\text{min}} = 10$
  - In hotspots, $\gamma_{\text{min}} \sim 100 - 1000$ required (e.g. Carilli et al. 1991)
  - Adiabatic expansion $\Rightarrow$ lower energy electrons in lobes

- Spectral index, $\alpha_{\text{low}} = 0.5$ (flattening)
  - Shock acceleration models predict $\delta = 2 - 2.3$
    (corresponding to $\alpha = 0.5 - 0.7$)
  - Also supported by hotspot observations (Carilli et al. 1991, Meisenheimer et al. 1997)
How assumptions about low-energy electrons affect the results

- For $\alpha_{\text{low}} = \alpha_{\text{obs}}$:
  - R values increase by a factor of $\sim 2$
  - increase in $U_{\text{tot}}$ of up to factor of 20
  - But prediction for IC/nuclear becomes significant
    $\Rightarrow B$ and $U_{\text{tot}}$ uncertain

- For $\gamma_{\text{min}} = 1000$ (instead of 10):
  - R values unchanged
  - IC/nuclear contribution decreases
  - Conclusions not affected

- For $\alpha_{\text{low}} \gg \alpha_{\text{obs}}$:
  - all bets are off!
Spatially resolved X-ray IC

- X-ray/radio ratio 3x higher close to nucleus compared to lobe centre.
- X-ray/radio ratio higher at edges of lobes.
- Radio spectrum steeper in inner regions
• **IC/nuclear?**
  - requires nuclear luminosity > $10^{40}$ W
  - expect counterjet side to have ~7 times more nuclear emission, but jet-side lobe has higher X/radio ratio

• **Variations in B?**
  - requires modest changes of factor ~ 1.5 in $B/B_{eq}$.
  - explains relatively uniform X-ray IC surface brightness
  - correlation between high X/radio ratio & steep radio spectrum requires larger variation in $B$

• **Variations in electron spectrum?**
  - With single $\alpha$ and $B$ along line-of-sight, can only obtain factor < 2 variation in X/radio ratio.
  - More detailed source model may help.

• **Conclusion:** variations in both $B$ and the low-energy electron spectrum are required.
Summary

• First X-ray IC survey of FRII population detects >70% of sources.
• For *reasonable* assumptions about the low energy electron population:
  – $B = (0.3 - 1.3) B_{eq}$
  – $U_{tot}$ typically within a factor of 2 of $U_{min}$
  – No energetically dominant proton population
• Detailed studies of individual sources (Isobe et al. 2002, Hardcastle & Croston 2005) imply spatial variations in both electron spectrum and B within lobes.
• 10 – 200 MHz observations essential to confirm these results: LOFAR will remove main uncertainties in constraining group/cluster energy input from FRIIs.
• LOFAR will also enable detailed spatial studies of electron and field distribution in radio lobes by probing same electron population as X-ray IC.