Magnetic fields and particle content in FRII radio sources

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Outline

- Introduction:
  - *B* fields and particle content of radio galaxies
  - X-ray IC as a probe of physical conditions
- Chandra archive survey
- Spatially resolved X-ray structure in Pictor A
- Conclusions: implications for jets and environmental impact

Magnetic fields and particle content

- Since *B* can’t be measured directly from radio emission, equipartition usually assumed.
- Particle content of jets:
  - Electron-positron?
  - Electron-proton?
- Entrained thermal material?
  - Probably dynamically important in FRIs (e.g. Croston et al. 2003)
  - Likely to be energetically unimportant in FRIIs based on limits from Faraday rotation and lack of spectral signatures (e.g. Celotti et al. 1998)

Hints about jet particle content: electron-proton jets?

- Annihilation of e± pairs near the nucleus means that e ± model only compatible with nuclear X-ray emission if $\gamma_{min} \sim 100$ (Ghisellini et al. 1992)
- Conservation of kinetic energy and number flux from pc to kpc scales favours e-p jets (Celotti & Fabian 1993)
- Talk by Ghisellini yesterday
- But, several arguments in favour of e± jets…

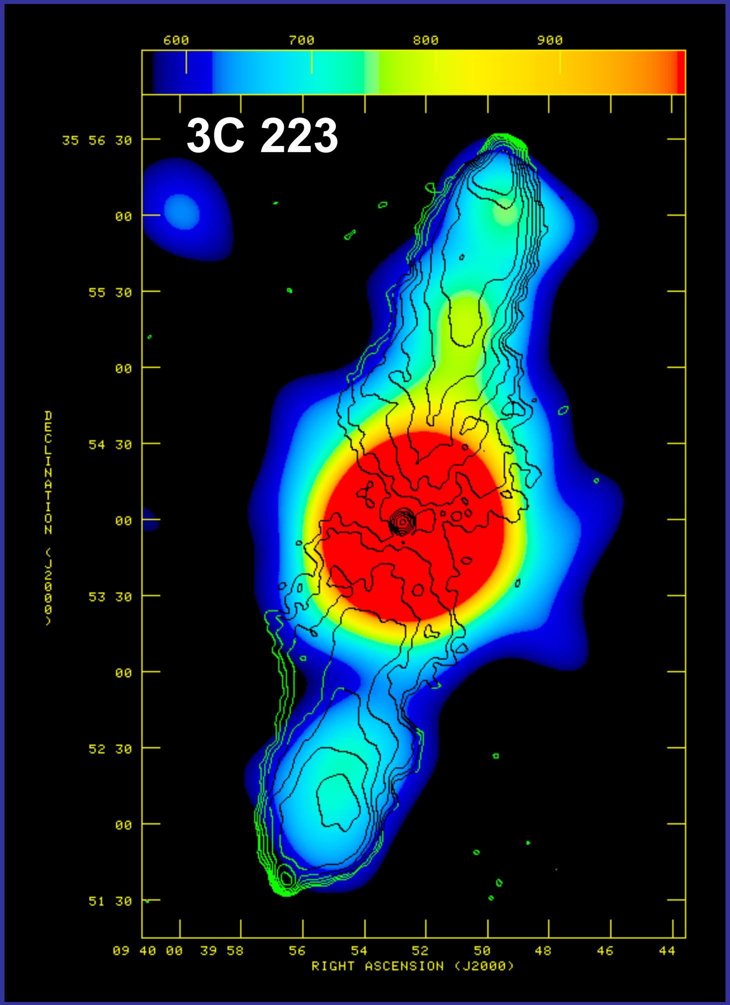
In favour of electron-positron jets

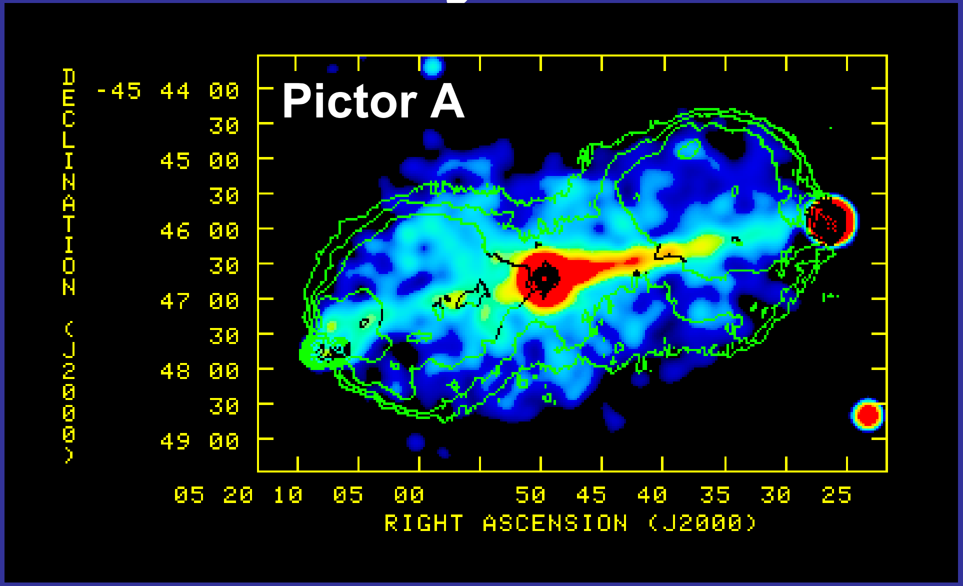
- Required energy budget for acceleration is lower
- Lack of Faraday depolarisation in parsec-scale jets => either high γ_{min} or e± (Wardle 1977, Jones & Odell 1977)
- Circular polarisation => low γ_{min} (e.g. Wardle et al. 1998; Homan 2005) if Faraday conversion (but see also Ruzskowski & Begelman 2002)
- Energetics of hotspots - combined analysis of shock conditions and IC emission (Kino & Takahara 2004) also supports e±
- Hotspots in the most powerful RGs close to equipartition with no protons…

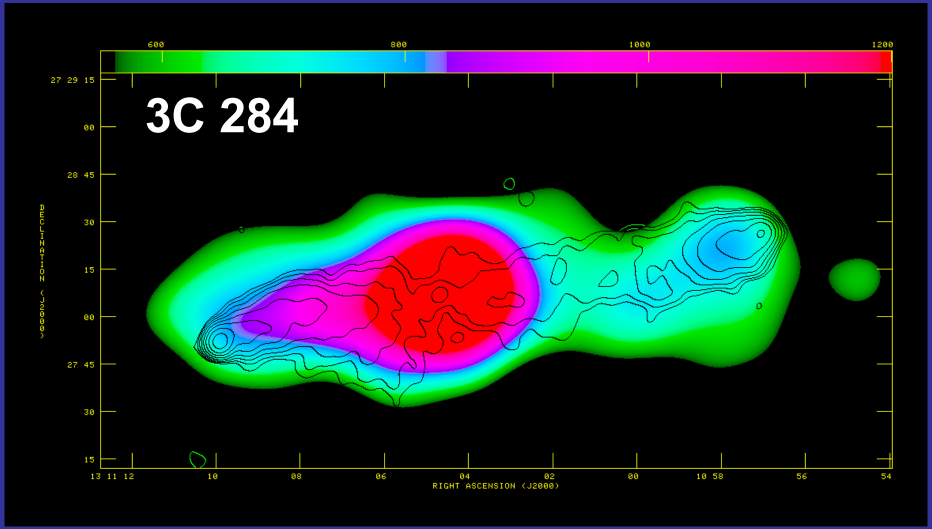
X-ray IC emission from radio lobes

- Inverse Compton process allows direct measurement of electron density => can calculate *B* from radio & test equipartition assumption.
- Equipartition with $\kappa=0$ would suggest no rel[c] protons
- Incident photon populations are CMB ($\nu \sim 10^{11}$ Hz) and nuclear IR/optical ($\nu \sim 10^{14}$ Hz) emission.
- $\nu_{out} \sim \gamma^2 \nu_{in}$ =>
  - To scatter CMB to X-ray, need $\gamma \sim 1000$
  - To scatter nuclear IR/optical to X-ray, need $\gamma \sim 30 – 100$
- Detected in a number of sources…

Detections of lobe X-ray emission







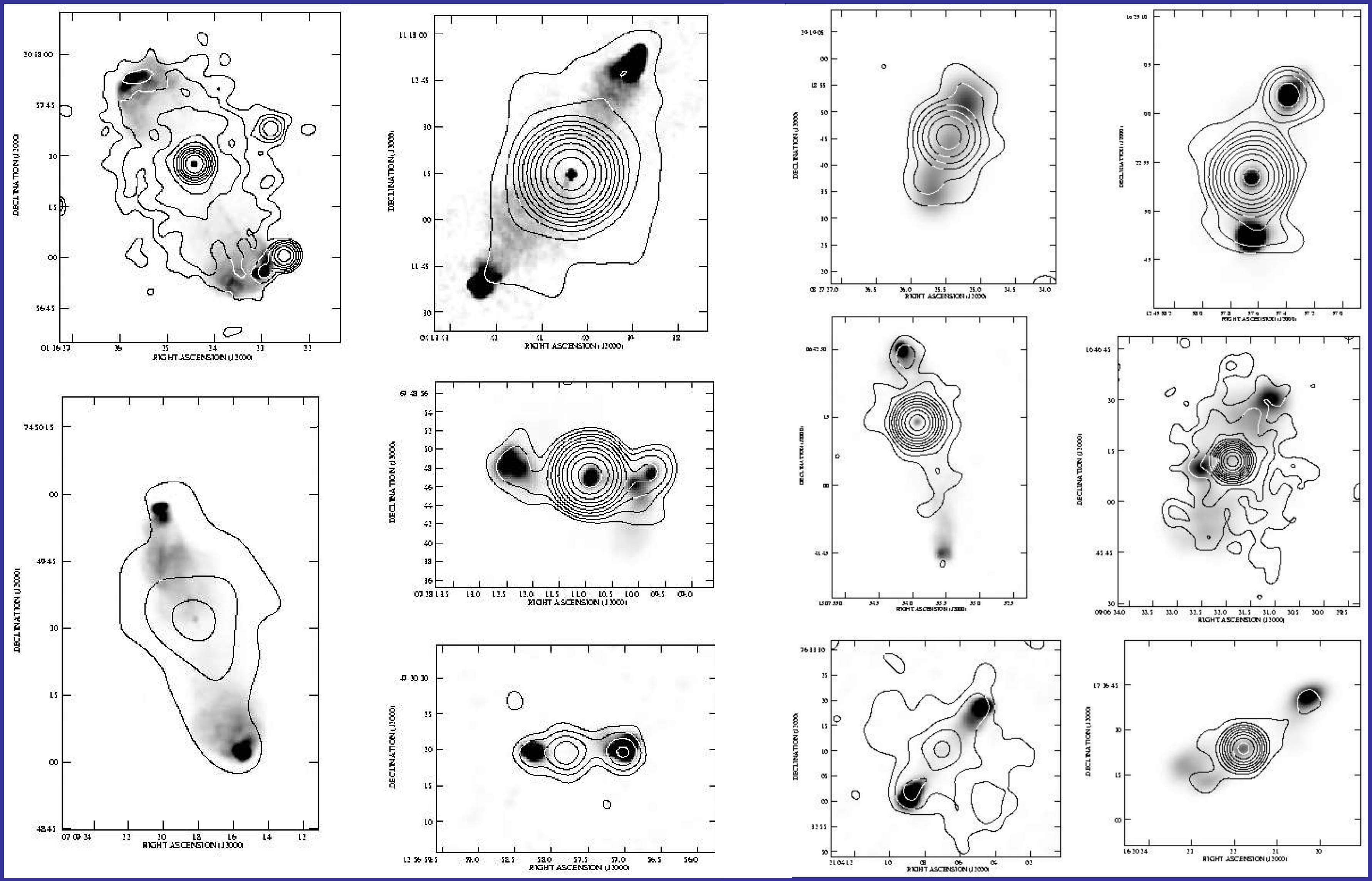
Croston et al. 2004, MNRAS 353 879; Hardcastle & Croston, submitted.

A survey of X-ray lobe emission

<u>Aim:</u> to constrain properties of entire FRII population

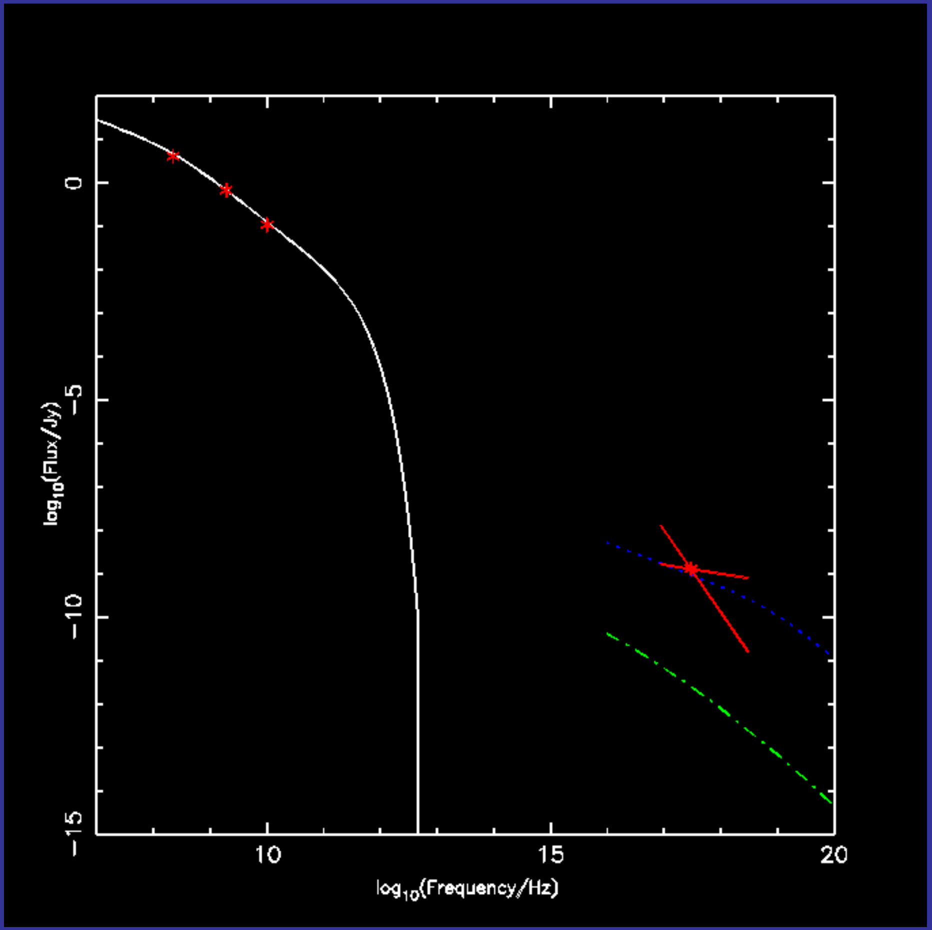
- All 3C radio galaxies for which public Chandra data existed at January 2004 + 4 XMM-observed sources.
- Exclude FRIs, sources in rich clusters, sources too small to separate AGN and lobe emission.
- Final sample:
  - 33 FRII radio galaxies and quasars
  - 54 lobes

11 new detections



IC analysis

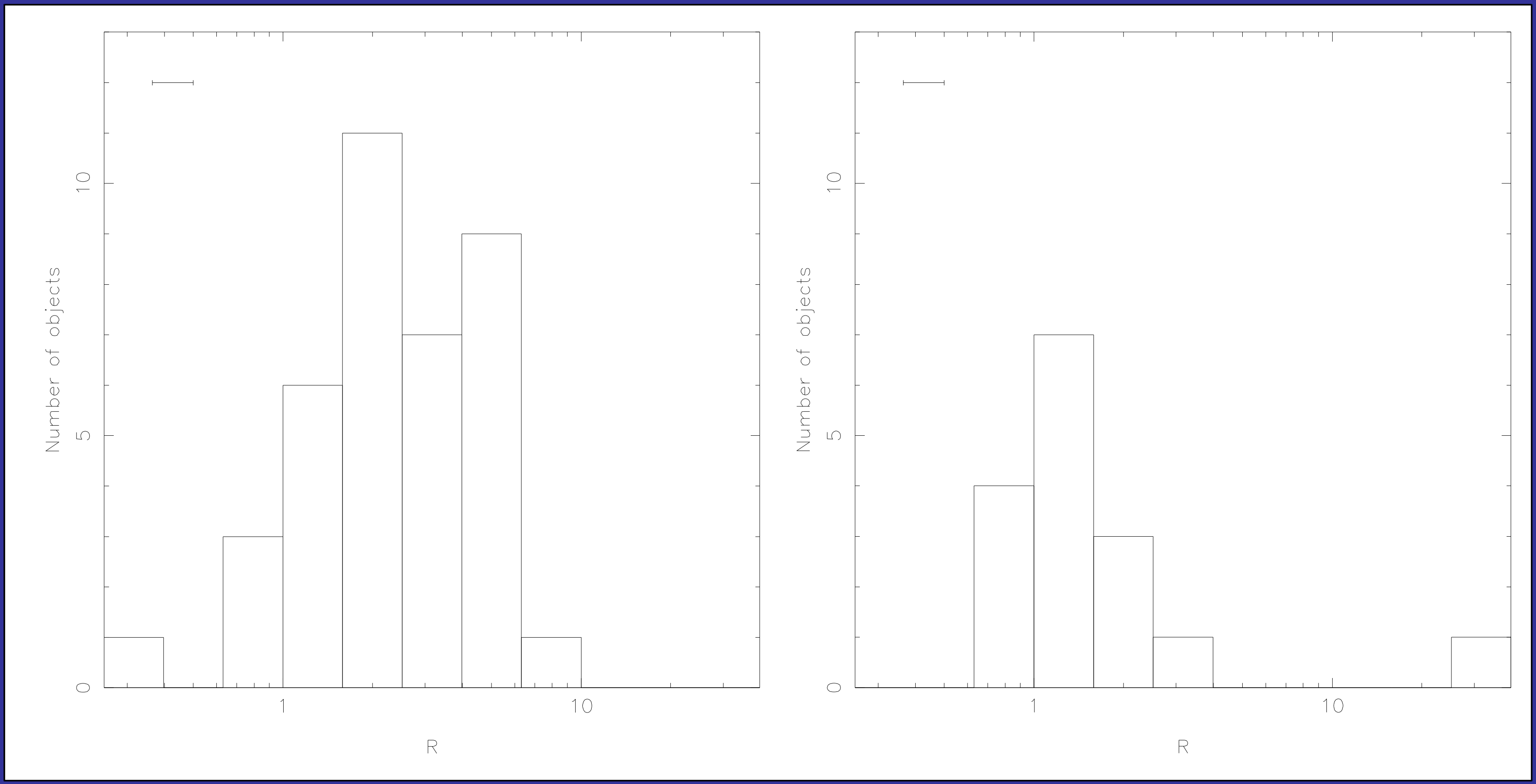
- Model electron population using radio spectrum:
  - 1.4 GHz maps with regions matched to X-ray extraction regions
  - 3C flux densities at 178 MHz
- Low-energy assumptions:
  - $\delta = 2$ (prediction from shock acceleration)
  - $\gamma_{min} = 10$
  - Spectral break $\Delta\delta = 1$
- Determine predicted X-ray IC/CMB emission at 1 keV for $B = B_{eq}$
- Define $R = S_{obs} / S_{pred}$



Assumptions about low-energy electrons

- Cut-off frequency, $\gamma_{min} = 10$
  - In hotspots, $\gamma_{min} \sim 100 - 1000$ required (e.g. Carilli et al. 1991)
  - Adiabatic expansion => lower energy electrons in lobes
- Spectral index, $\alpha_{low} = 0.5$ (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)
- Spectral break
  - fit curvature of spectrum, caused by ageing => one-zone model is a poor approximation!

Distribution of R (S_{obs}/S_{pred})



Detections

Non-detections

Statistical properties of the sample

- No correlations between *B* and:
  - Radio luminosity (cf. hotspots => synch comp.)
  - Angular size
  - Physical size
  - Redshift
- BUT, possible difference between RGs and quasars…

Narrow-line vs. broad-line objects

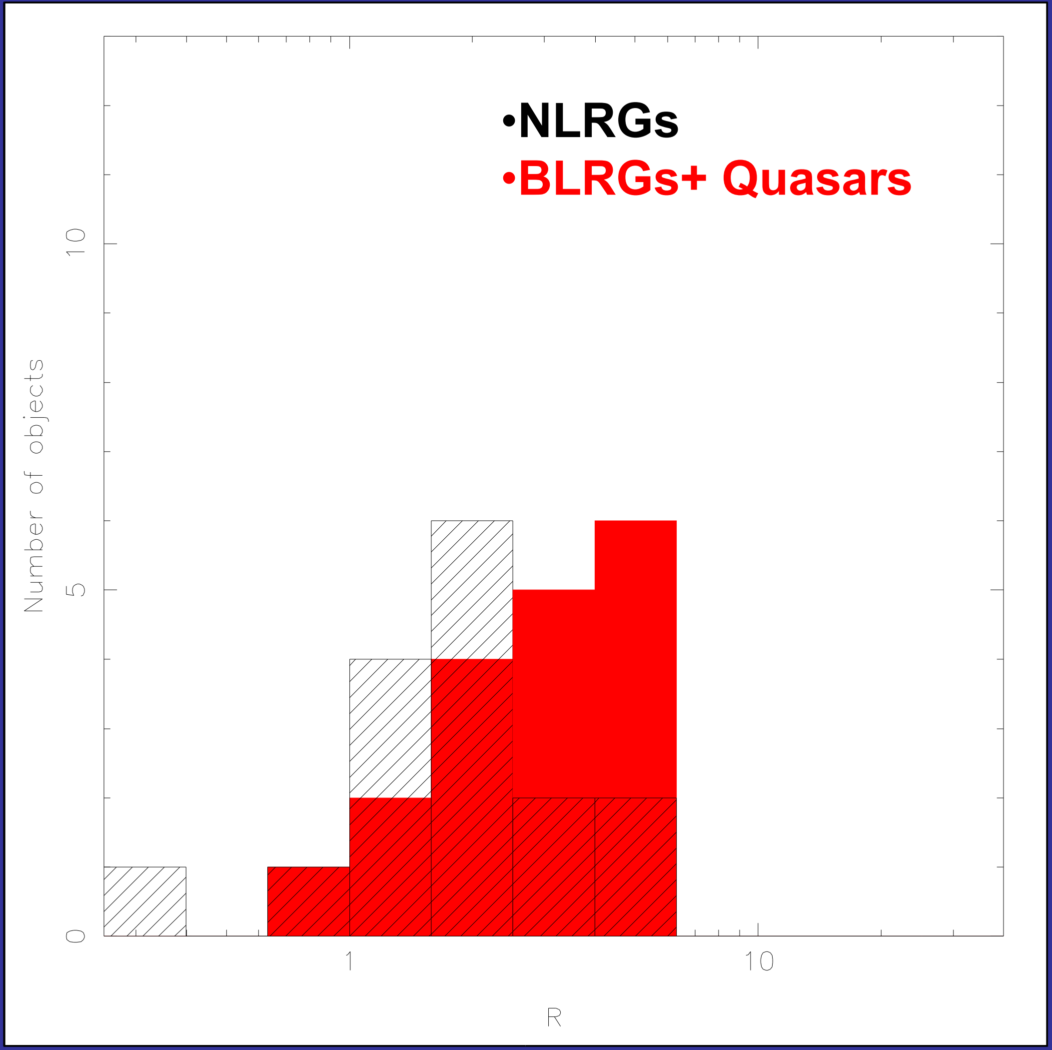
Narrow-line radio galaxies:
 θ > 45º

Broad-line radio galaxies & quasars:

θ < 45º

Unlikely there is problem for unification:

- **Projection:** volume systematically underestimated with increasing angle.
- BLRGs & quasars more distant: **worse systematics** in X-ray analysis, e.g. separation of lobe & AGN emission.



Results

see Croston et al. 2005 (ApJ 626, 733)

- X-ray detection of at least one lobe for 70% of sources.
- Consistent with IC/CMB with $B = (0.3 – 1.3)\ B_{eq}$
- 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.

Particle content and energetics

- If $B \sim B_{eq}$, then energetically dominant proton population unlikely - would require a mechanism to achieve $U_B \sim U_E$, rather than $U_B \sim U_{E+P}$.
- Total internal energy in FRII radio sources typically within a factor of 2 of minimum energy.
- Where environments have been measured, internal $P_{eq} \sim P_{ext}$ => pressure balance (e.g. Hardcastle et al. 2002, Croston et al. 2004, Belsole et al. 2004)

What about IC/nuclear emission?

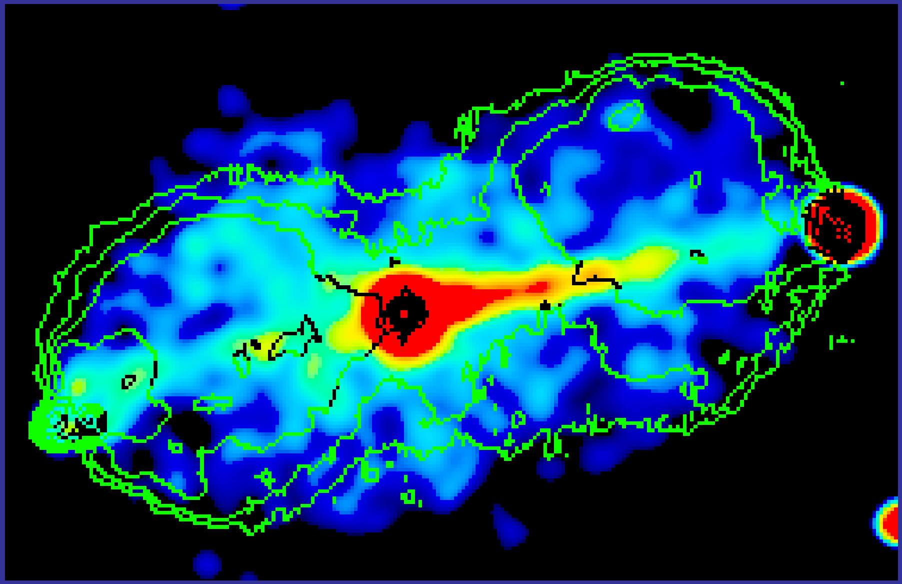
- Brunetti et al. (1997) argue that scattering of nuclear IR/optical photons is also important.
- Claimed detections in several sources (e.g. Brunetti et al. 2002, Bondi et al. 2004)
- For our assumptions about low-energy electrons, we find predicted $S_{nuclear} << S_{cmb}$.
- But, this prediction depends even more strongly on the assumptions about low-energy electrons ($\gamma \sim 30 - 100$ dominates here)…

Dependence on low-energy electron parameters

- For $\alpha_{low} = \alpha_{obs}$:
  - R values increase by a factor of ~ 2
  - increase in U_{tot} of up to factor of 20
  - But prediction for IC/nuclear becomes significant => <u>*B* and U_{tot} uncertain</u>
- For $\gamma_{min} = 1000$ (instead of 10):
  - R values unchanged
  - IC/nuclear contribution decreases
  - Conclusions not affected
- For $\alpha_{low} >> \alpha_{obs}$:
  - all bets are off!

A more in-depth look: Pic A

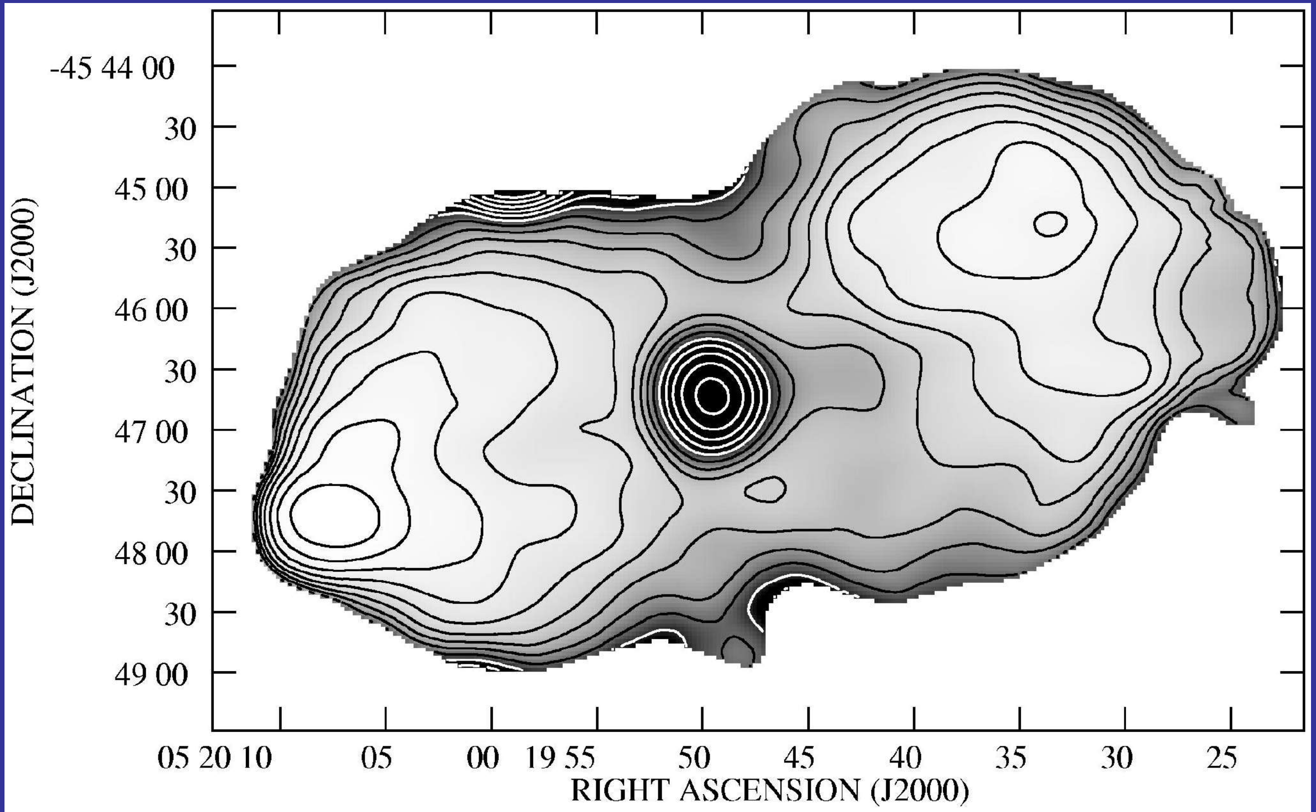
- 8th brightest radio source in the sky at low frequencies.
- z =0.035
- Little thermal X-ray emission to complicate analysis.
- 3 archive Chandra observations & one archive XMM observations.



Hardcastle & Croston 2005, MNRAS, sub.

Spatial structure

- X-ray/radio ratio higher by up to factor 3 close to the nucleus relative to lobe centre.
- X-ray/radio ratio higher at edges of lobes.
- NB. Radio spectrum steeper in inner regions.



Possible interpretations

1. Additional emission process in the inner regions
2. Variations in B/B_{eq}, so that inner lobes are more electron-dominated.
3. Radio measurements underestimate low-energy electrons in centre compared to outer regions

1. Additional emission process

- Thermal emission?
  - Can be ruled out based on spectral analysis of inner and outer regions
- Nuclear IC?
  - Requires nuclear luminosity > 10^{40} W
  - Expect counterjet side to have ~7 times more nuclear emission
  - In fact, jet-side lobe has larger high X/radio ratio

2. Variations in B/B_{eq}

- Modest changes of factor ~ 1.5 needed
- *B* closer to equipartition nearest hotspots, falling to lower values in distant (older?) part of lobes
- Low-energy electron population is the same throughout lobes => explains relatively uniform X-ray IC surface brightness.
- Cannot explain the correlation between high X/radio ratio & steep radio spectrum (would require larger variation in *B*).

3. Variation in electron spectrum

- Changes in low-frequency spectral index should only produce at most factor ~2 variation in X-ray/radio ratio.
- Assumes single spectral index and *B* along line-of-sight => more detailed source model may help.
- <u>Conclusion:</u> variations in both *B* field and the low-energy electron population are required.

Summary

- X-ray IC emission from radio lobes allows us to measure n_e and B directly and investigate particle content.
- First survey of FRII population as a whole shows:
  - More than 70% of sources are detected
  - $B = (0.3 - 1.3)\ B_{eq}$
  - U_{tot} typically within a factor of 2 of U_{min}
  - No energetically dominant proton population
- In-depth look at Pic A reveals a more complicated situation:
  - Variations in both magnetic field strength and low-energy electron population are likely to be important

Implications for jet physics and environmental impact

- Jets:
  - Energetically dominant relativistic protons unlikely
  - Combined with earlier evidence against cold protons and hotspot results

    => **strong argument that FRII jets are e±**
- Environmental impact:
  - Justification for modelling FRII dynamics and evolution using equipartition assumption
  - FRIIs not supersonically expanding?
  - Total energy budget available for transfer to cluster environment constrained close to minimum value